

A NEW ERA OF DIGITALISATION FOR OCEAN SUSTAINABILITY?

PROSPECTS, BENEFITS,
CHALLENGES

OECD SCIENCE, TECHNOLOGY
AND INDUSTRY
POLICY PAPERS

May 2021 **No. 111**

This paper was approved and declassified by written procedure by the Committee on Scientific and Technological Policy on 7 April 2021 and prepared for publication by the OECD Secretariat.

Note to Delegations:

This document is also available on O.N.E under the reference code:

DSTI/STP(2021)2/FINAL

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Acknowledgements

This paper summarises research and analysis conducted by the Ocean Economy Group in the Directorate for Science, Technology and Innovation (STI) on digitalisation trends in the ocean economy, particularly as they impact ocean observing systems. This paper was initially drafted by Barrie Stevens, Consultant / Senior Adviser to the Secretariat, with contributions from Claire Jolly and James Jolliffe of the STI Ocean Economy Group, in the Science Technology Policy Division (STP). Chrystyna Harpluk provided editorial assistance.

The paper builds on findings from two OECD expert workshops held in 2019 and 2020, which included more than fifty expert presentations from leading scientists and technologists in the marine domain.

- A first OECD foresight workshop was held in Brussels, on 20-21 November 2019 which explored the development of digital technologies in the ocean economy over the next eight years, and the potential scope for their application across a range of operational uses. The workshop was jointly organised by the OECD STI Ocean Economy Group, the Flemish Blue Cluster and the Flanders Marine Institute, and supported by the Department of Economy, Science and Innovation of the Flemish Government (EWI).
- A follow-up OECD workshop was held on 30 September 2020 on ‘Linking economic potential and marine ecosystem health for sustainable development through marine spatial planning’. This joint OECD - UNESCO - Bluemed workshop was hosted virtually by the Stazione Zoologica Anton Dohrn in Naples in the context of the Naples Shipping Week, in cooperation with the Marine Sciences Research Institute (ISMAR) of the Italian National Research Council (CNR) and the Italian Blue Cluster.

The scientists, technological experts and policy representatives from research centres, universities and industry who contributed are kindly thanked for sharing their expertise; they are acknowledged in the text. Special thanks go also to Asgeir Sørensen from the Norwegian University of Science and Technology for his detailed comments on previous drafts and to Emma Heslop from UNESCO’s Intergovernmental Oceanographic Commission.

This original work on the ocean economy would not exist without the continued support, generous expertise and invaluable advice provided by the Steering Board of the OECD STI Ocean Economy Group Innovation and the Ocean Economy project. The current and past Steering Board members particularly contributing to this work stream are: Gert Verreet (DESI, Flanders, Belgium); Rasmus With (DMA, Denmark); Niall McDonough and Jenny O’Leary (Marine Institute, Ireland); Marco Borra (SZAD, Italy); Jeong-In Chang (KMI, Korea); Christina Abildgaard (RCN, Norway); Conceição Santos (DGPM, Portugal); Sofia Cordiero (FCT, Portugal); and, Monica Grasso (NOAA, United States).

We also thank delegates of the OECD Committee for Scientific and Technological Policy (CSTP) and other national delegates for their support to this activity.

Executive Summary

Growing worldwide acknowledgement of the importance of our ocean and seas for the future of humanity draws ever more attention to the need for sustainable use of the planet's marine resources. Without a healthy ocean and productive seas, the task of providing oxygen from primary production, and generating food, energy and jobs for the world's population, while effectively addressing climate change and biodiversity, will prove all the more challenging. Hence the importance of achieving a sustainable balance between the use of ocean resources and their protection and restoration. Reaching and conserving that balance will require a major global effort, as reflected in the United Nations (UN) Sustainable Development Goals (SDGs) and in particular SDG 14, namely conserve and sustainably use the oceans, seas and marine resources for sustainable development.

Good governance, effective management, smart policies and the engagement of many sectors of society, all have their part to play. But so do science and technology. Indeed, they form a keystone in any global ocean sustainability strategy, as conveyed in the context of the UN Decade of Ocean Science for Sustainable Development.

Digital technologies hold great promise for ocean sustainability. Artificial Intelligence (AI), cloud computing, the Internet of Things (IoT), processes automation, robotics, high-performance sensors, have been rapidly diffusing throughout the economy and been integrated into a multitude of applications old and new. However, in many areas of the ocean economy their uptake has been markedly slower. That now appears to be changing. There are strong signs that the pace of digital innovation is set to accelerate in the ocean economy. Taking a longer-term view, the widespread diffusion of such technologies holds out the potential to reshape the performance, efficiency and location of many ocean activities, create new ones and contribute significantly to ocean sustainability.

This paper explores the potential contribution of digital technologies to ocean sustainability - especially those that apply to the field of ocean observation. As a result, the paper:

- explores likely advances in science, technology and innovation over the next 8 to 10 years which should lead to substantial improvements in the collection of data on, and analysis of, the impact of climate change and human activity on marine ecosystems, while also help the monitoring and reduction of the ecological footprint of economic activity in the ocean;
- identifies and discusses the steps required to sustain the current innovation momentum in the digital ocean economy, since it cannot be assumed that the considerable potential of such innovations can be fulfilled without considerable additional efforts on multiple fronts;
- sets out preliminary reflections on how the Covid-19 pandemic might affect the pace of digital innovation in the ocean economy, and what strategies might be pursued to advance ocean research and innovation during and in the aftermath of the pandemic.

Several innovations in ocean-related data collection and analysis are in the pipeline or already coming on stream and have the potential to make a significant impact in the course of the next decade. There are four areas of rapid technological advancement: ocean sensing and imaging instruments benefitting from artificial intelligence and machine to machine communication; the expanding spatial

coverage of float arrays and fixed observation platforms; the increasing autonomy in mobile platforms; and new complex systems integration schemes. Science and technology in all of these areas are able to demonstrate impressive advances in digital innovation in ocean observation. Combining all of these advances into a functioning and effective digital system of ocean data collection, analysis and action holds great promise for the medium- and longer-term future of a sustainable ocean economy. However, many of those innovations will not come to fruition or find widespread use entirely of their own accord. They will require strong supportive, organisational and collaborative action in a wide range of areas.

A range of measures are required to sustain over time the current pace of digital innovation in the ocean economy.

They comprise measures to reduce the cost of innovating and scaling up production, including the creation of new markets and the testing of new business models for ocean observation systems, introducing new forms of collaboration in ocean technology development, improving ocean literacy for accessing risk capital, and achieving greater standardisation of technology processes and products to push down costs.

In addition, actions can be taken to broaden and deepen industry-science collaboration with a view to extending coverage of ocean observation. Opportunities increasingly present themselves for co-operation with various offshore industries, telecommunications cable companies, the fisheries sector and the tourism and leisure industries.

Finally, efforts are required to change the ocean data paradigm to reap the benefits of long term investments. This can be achieved through improved access to and sharing of ocean data, greater standardisation of data and interoperability, improved use of best practices as the foundation for standards, accompanied throughout by enhancements in data integrity and security.

However, the pursuit of these measures is likely to be significantly challenged by the effects of the Covid-19 pandemic. The pandemic strikes at a particularly delicate moment in time. Significant advances in digital technology for ocean-observation are on the verge of widespread implementation, and the UN Decade of Ocean Science for Sustainable Development is beginning, which holds out the prospect of a massive boost to ocean science in the next ten years. The threat posed by Covid-19 to future investment in science for the ocean in general, and in ocean observation in particular, is that government and private-sector responses to the pandemic could lead to a diversion of human and financial resources and – perhaps even worse over the longer term – to budget cuts in ocean research.

Should such a scenario of tighter budgets and key resource diversion become a reality, policy-makers and the ocean science community needs to stand ready to implement alleviating measures. It is important that the potential sustainability gains to be derived from recent scientific, technological and organisational advances are not seriously compromised and that creative solutions are found to maintain and improve the efficiency and effectiveness of ocean research activities. Such measures could include efforts to:

- leverage existing infrastructures and ocean observation networks, and expand user engagement;
- reduce cost and scaling up production volumes of sensors and other instruments, and focus on low-cost solutions where possible;
- strengthen industry-science collaboration to expand ocean observation coverage, especially to address the current highly uneven geographical distribution of knowledge, know-how and technologies.
- improve access to and sharing of data via standardisation, interoperability and best practices, especially where they promise considerable cost-savings and efficiency gains
- And strengthen horizon scanning for innovations and existing technologies that might be adapted to ocean research purposes.

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1 Introduction and general context

The ocean is increasingly perceived as a new economic frontier, offering the prospect of large resource wealth and the generation of substantial economic activity, employment and innovation (OECD, 2016^[1]). At the same time, it has the potential to help address many of the global challenges facing the planet, from oxygen production from primary sources, food security, energy provision and natural resources to climate change and human health. However, the ocean and its ecosystems have been under considerable and growing pressure for decades as human activity and anthropogenic climate change have continued to augment their impact on ocean health. Those impacts are set out in great detail in the Intergovernmental Panel on Climate Change (IPCC) report on the ocean and cryosphere in a changing climate (Pörtner, 2019^[2]). What has been attracting ever more interest are the cumulative effects of those impacts. Halpern et al. (2019^[3]), for example, estimate that 59% of the ocean has already been experiencing a significant rise in cumulative effects over the 11-year period from 2003 to 2013, while at the same time only 5% of the ocean experienced a decrease in such pressures. According to Halpern and colleagues, almost all countries witnessed increases in cumulative impacts in their coastal waters, with outcomes such as growing biodiversity loss, important geographical and seasonal shifts in main species, loss of coral reefs and mangroves, and much more..

Yet human activity in and on the ocean is expected to grow further as existing ocean-based industries expand, while new industries emerge and develop (e.g. seabed mining, offshore aquaculture, marine renewable energy). First and conservative estimates of the size of the ocean economy, in terms of its industries, suggest that it is likely to double in size between 2010 and 2030 (OECD, 2016^[1]). The Covid-19 pandemic is likely to slow down that growth to some extent. As a consequence, marine ecosystems face unprecedented and cumulative pressures in the coming decades from both human activity and climate change (Jouffray et al., 2020^[4]; Duarte et al., 2020^[5]). If ocean-based economic activities are to respond meaningfully to the demands of a growing world population, they will need to work in a sustainable way with marine ecosystems.

Striking an appropriate balance between expansions of ocean-based activities on the one hand and ensuring a healthy ocean on the other will require responsible, effective, sustainable approaches. The broad picture of how this might be achieved is set out to a large extent in the UN's Sustainable Development Goals (SDGs), and in particular in SDG 14. In light of the unprecedented cumulative pressures building up on marine ecosystems, however, conservation alone is unlikely to be enough. Indeed, as many experts emphasise (Duarte et al., 2020^[5]), the ultimate objective needs to be the restoration of ocean health, so as to ensure marine ecosystems can indeed sustainably support the growing needs of an additional 2 to 3 billion people. Such a strategy would include not only tackling major threats to ocean health from such sources as pollution, macro- and micro-plastics, etc., but also increasing the abundance of key habitats and keystone species, and restoring marine ecological structure, functions, resilience and ecosystem services.

A precondition for meeting those objectives is a far better understanding of how humanity is affecting the oceans, which in turn requires much greater knowledge about the pace of change in the cumulative impacts on marine ecosystems from expanding human activities (Halpern et al., 2019^[3]). Actions will need to be

evidence-based and built on extensive, high-quality, reliable data, much of which will require large inputs from ocean research and observation. Considerable impetus to such efforts can be provided by the advent of the UN Decade of Ocean Science for Sustainable Development.

The aim of this paper is threefold:

- to explore likely advances in science, technology and innovation over the next 8 to 10 years which should lead to substantial improvements in the collection of data on, and analysis of, the impact of climate change and human activity on marine ecosystems, while also monitoring and helping reduce the ecological impacts of economic activity in the ocean;
- to identify and discuss the steps required to sustain the current innovation momentum in the digital ocean economy, since it cannot be assumed that the considerable potential of such innovations can be fulfilled without considerable additional efforts across a range of issues;
- and, to set out some preliminary reflections on how the Covid-19 pandemic might affect the momentum of digital ocean innovation, and what strategies might be pursued to advance ocean research and innovation in the greatly changed context of the pandemic.

The initial building blocks for this paper were laid out by the presentations and discussions at an OECD Foresight Workshop held in Brussels on 20-21 November 2019. The workshop was entitled “Digital Technologies in the Ocean Economy: Exploring the Future” and it was jointly organised by the OECD STI Ocean Economy Group, the Flemish Blue Cluster and the Flanders Marine Institute, and supported by the Department of Economy, Science and Innovation of the Flemish Government (EWI). It was held in connection with the 2019 Global Sustainable Technology and Innovation Conference (G-STIC).

The paper also builds on a second OECD workshop held on 30 September 2020 on linking economic potential and marine ecosystem health for sustainable development through marine spatial planning. This joint OECD - UNESCO - Bluemed workshop was hosted virtually by the Stazione Zoologica Anton Dohrn in Naples in the context of the Naples Shipping Week, in cooperation with the Marine Sciences Research Institute (ISMAR) of the Italian National Research Council (CNR) and the Italian Blue Cluster.

2 Innovations in ocean-related data collection and analysis for the next decade

2.1. The expanding potential of ocean observation

A scientific understanding of the ocean in terms of its properties and behaviour, its health, its influence on weather, and its role in climate change and biodiversity, is critical to understanding and managing marine ecosystems. By the same token, it is a vital pre-condition for understanding the impact of ocean-based industries on the marine environment and therefore, by extension, for assuring the sustainable use of our ocean and seas in the coming years.

The foundation for that understanding is the sustained acquisition of accurate, reliable and replicable scientific ocean data relating to a wide set of phenomena and issues. These include for example: climate change, rising sea temperatures and sea levels; ocean acidification and de-oxygenation; pollution; declining fish stocks; and the loss of coastal habitats. Monitoring, quantifying, tracking and forecasting such a complex array of stressors and their impact on marine ecosystems requires multidisciplinary and transdisciplinary approaches to ocean observation. The Global Ocean Observing System's (GOOS) Essential Ocean Variables (EOVs) provide a framework for assessing what should be observed and/or monitored based on relevance, impact and feasibility, helping to drive observation technology development towards the most effective areas. Other forces impacting on observation technology development include environmental and social objectives such as the European Union's Marine Strategy Framework Directive and, more recently, the UN's SDGs (especially but not only SDG 14). The needs of industry constitute a further driver, with the potential to become an increasingly important factor in the future development of relevant technologies.

Despite low levels of investment in ocean observing systems, observation of Essential Ocean Variables in the domains of ocean physics and biogeochemistry has progressed quite well, not least because the sensor technologies involved are at an advanced level of maturity. However, it is not yet feasible to measure all at scale and cost-efficiently all variables, particularly those related to biology, and also to ecosystems which have not traditionally been a focus of ocean observations (Table 1). With the emergence of new and improved technologies, a renewed effort is underway to expand the collection of information on biology and ecosystem characteristics. Biological Essential Ocean Variables have been established by the Global Ocean Observing System Biology and Ecosystem Panel, covering data on status and trends in the abundance, distribution and genetic diversity of species such as microbes, phytoplankton, zooplankton, benthic invertebrates, fish and mammals (GOOS, 2017^[6]). Ongoing work in developing further observing networks and the coordination of existing observing programmes into global networks is underway.

The measurement of biological variables in sustained ocean observing systems will close some of the considerable knowledge gaps in the field. To a large extent, the present situation has to do with problems

of accessibility and the uneven distribution of sea life. The deep sea is a case in point. Unlike high-biodiversity ecosystems such as rain forests and coral reefs, little is known about life on the deep seafloor. Access is extremely difficult, and organisms in all their forms – whether viruses, microbes or megafauna – tend to occur in low densities. This leads to relatively limited numbers of standardised survey samples, hampering potential extrapolation of species richness over large areas of the deep sea (Brandt et al., 2016^[7]).

In part, however, the knowledge gaps are also related to technological shortcomings. Notably on the marine biology front, the technology for periodic observations has lagged behind capabilities for measuring physical and biogeochemical properties of the ocean. Notwithstanding the existence of various individual, highly selective sampling programmes, the current set of observations is considered on the whole to be insufficient for measuring, characterising and monitoring sea life on a global scale or indeed on most regional scales (Muller-Karger et al., 2018^[8]). This applies equally to deep-sea ecosystems where, as things currently stand, monitoring of all size classes of organisms at different spatial and temporal scales is lacking (Brandt et al., 2016^[7]).

Given the scale and complexity of modelling, measuring and monitoring the physical, chemical, biological and ecosystem variables of the ocean in a more comprehensive and more efficient manner than hitherto, considerable advances in science, technology and innovation will be required. Progress is needed on at least two levels, instrumentation and infrastructure. In both, digital technology is a powerful driver. Innovations in Artificial Intelligence (AI), cloud computing, automation, robotics, the Internet of Things (IoT), to mention but a few, have been gaining ground quickly in almost all sectors of the wider economy. There are now strong signs that the pace of digital innovation is set to accelerate in the ocean economy, too. On the instrumentation side, sensors and imaging are benefitting markedly from the drive towards miniaturisation (even down to the size of miniature autonomous underwater explorers to study plankton) and automation, the growing demand for low-power, low-cost devices for the measurement and graphic display of the physical environment, and progress in endowing the sensor itself with “intelligence” (OECD, 2016^[11]). Further progress is also being made in combining numerical ocean and ecosystem simulation models with extended and improved sampling capabilities. Examples include Norway’s [SINTEF SINMOD](#) and NOAA’s [HYCOM models](#) in the United States.

On the infrastructure side, the already wide and diverse range of infrastructures required to perform modern ocean observation is set to benefit from further expansion and technological sophistication. Coastal and deep-sea observatories, sensor-equipped power and communication cables, floating and submersible vehicles and sensor-carrying platforms, ocean-going research vessels, coastal radar, satellite remote sensing, communications and global positioning, drones, modelling and computational infrastructure, and big data storage and management – all stand to gain from future enhancements.

So far, improvements in, and the growing diffusion of, sensor systems have gone hand in hand with improvements in the numbers and operational capacities of marine platforms. Looking to the future, it is to be expected that further investments, and technological advances in instrumentation and infrastructure alike will feed off each other. Unsurprisingly therefore, the notion of an impending “ocean data explosion” in the coming decade appears to be gaining ground. However, making sense of and effectively utilising increasingly massive volumes of data collected from the ocean is thought to be well beyond the capabilities of traditional analytical methods. Artificial intelligence (AI), for example, is proving its worth in analysing big data in multiple sectors and is increasingly being transferred and adapted to marine applications.

Many technical issues remain to be resolved regarding marine big data, not least the creation of large-scale modern data infrastructures combining big data storage, high-powered computing, and new analytical methods to support decision making, particularly for practical use in marine spatial planning (Liu et al., 2017^[9]). Furthermore, innovation will be required in such matters as enhanced interoperability, data standards and best practices (Buck et al., 2019^[10]). Once interoperable infrastructures are in place,

technologies associated with AI such as machine learning would certainly seem to offer considerable potential for the effective analysis and quality control of marine big data. At the moment, the main application of machine learning in ocean science is identifying objects within images (e.g. automatically identifying certain types of coral) or learning from numeric patterns in long-term environmental time series in order to identify patterns in large volumes of other data. However, the technology is anticipated to eventually provide a whole range of tools needed to solve many of the complex challenges confronting marine science and resource management (Malde et al., 2020^[11]).

This section of the paper explores likely advances in science, technology and innovation that should lead to improvements in the capture of data on, and analysis of, the impact of climate change and ocean economic activity on marine ecosystems, as well as in monitoring and helping reduce the ecological footprint of economic activity in the ocean. The focus here is on four broad areas of technological advancement: ocean sensing and imaging; the expanding spatial coverage of float arrays and fixed observation platforms; increasing autonomy in mobile platforms; and systems integration.

2.2. Ocean sensing and imaging – the advent of a new era?

New smart sensors, processes and techniques are generating significant improvements in sensitivity, accuracy, stability and resistance to harsh ocean conditions. Since the 1990s there has been steady progress in automated sensing of key physical features such as current, salinity and temperature, and the last decade has seen advances in the form of novel in-situ sensors capable of monitoring some biochemical and biological features such as nitrates, methane and micro-nutrients. However, as Table 1 illustrates, specifically on biological and ecosystem-related sensors there is still a long road ahead.

Table 1. Essential Ocean Variables (EOVs) in physics, biochemistry, biology and ecosystems, and technological readiness levels

Physics	Biogeochemistry	Biology and ecosystems
Sea state	Dissolved oxygen	Phytoplankton biomass and productivity
Ocean surface vector stress	Inorganic macro nutrients	Harmful algal bloom incidence
Sea ice	Carbonate system	Zooplankton diversity
Sea surface height	Transient tracers	Fish abundance and distribution
Sea surface temperature	Suspended particulates	Apex predator abundance and distribution
Subsurface temperature	Nitrous oxide	Live coral cover
Surface currents	Carbon isotope	Sea grass cover
Subsurface currents	Dissolved organic carbon	Mangrove cover
Sea surface salinity		Macroalgal canopy cover
Subsurface salinity		
Heat flux/radiation		

Note: The colour of the text represents the technological readiness level of the variable. Green represents mature technological readiness. Orange represents pilot technological readiness. Red represents concept technological readiness.

Source: Adapted from Delory (2019^[12]).

Sensors are reducing in size and power requirements, and the use of lower-cost materials is increasing, thereby reducing the costs of data collection and allowing more data to be collected over longer periods of time. At the same time, automation, multi-sensor integration and multifunctionality have been improving, as has lab-on-chip technology. Box 1 offers an overview of the evolution in a wide range of key state-of-the-art technologies.

The current state-of-the-art in many sensor technologies may become relatively commonplace in the next decade thereby improving upon present-day ocean observation capabilities. Extending the deployment of modern sensors to citizen science activities and to developing countries will further increase coverage. However, and notwithstanding the considerable scientific and technological advances that have been made in recent years, it is widely acknowledged that the magnitude of the big scientific issues of the day in dealing with the vastness and variability of the ocean, and the need to cover both short-term changes and long-term trends in the most appropriate locations, pose huge logistical and economic challenges to comprehensive ocean observation. New technologies, integration of data and model information, and new strategies are needed to achieve the order of magnitude increase required in temporal and spatial coverage.

Numerous technical challenges are likely to remain for at least the medium term, i.e. the coming decade (Delory, 2019^[12]). These include inter alia the need to:

- increase sensor system's **spatial and temporal resolution**;
- augment the depth range for biogeochemical, biology and contaminant sensors, including by improvements in pressure and corrosion resistance;
- enhance the **reliability and stability** of sensors for measuring biology and ecosystems;
- further reduce the **size**, and thereby further increase the integration capacity, of sensors;
- achieve lower **power consumption** of sensors and thereby increase operating times;
- reduce/prevent physical and biological fouling;
- improve **sensor and data interoperability** across domains and platforms;
- further **reduce the environmental cost of observing** (recoverable systems, biodegradable materials, improved rechargeable batteries, use of renewables, etc.).

Greater recognition of the importance of coordinated strategies will also be required. These range from greater collaboration across borders and disciplines, and improvements in standards and best practice, through acceleration of technology transfer to users and greater engagement of citizen science, to expansion of synergies among stakeholders and open data policies. Some in the international ocean observation community consider that, among the most important challenges to be addressed, is the development of strategies to dramatically reduce the cost of ocean observation sensors and deploy them in more cost-effective ways, thereby boosting substantially the spatial and temporal coverage of future ocean observing (Wang et al., 2019^[13]; Levin et al., 2019^[14]), and Section 3 of this paper).

Box 1. Overview of some key state-of-the-art technologies

Biogeochemistry

New optical and electrochemical sensors for biogeochemistry are emerging (Delory, 2019^[12]); (Mowlem 2019). These include autonomous in situ nutrient electrochemical sensors for measuring silicate and phosphate down to a depth of 600 meters, as well as nutrient sensor modules for detecting nitrate (Delory, 2019^[12]); miniature optodes attachable to marine organisms for measuring dissolved oxygen, and handheld seawater pH sensors for marine carbon sampling (Wang et al., 2019^[13]); lab-on-chip technology for detection and measurement of pH and dissolved inorganic carbon (Wang et al., 2019^[13]); lab-on-chip chemical sensors for measuring multiple nutrients - pH, nitrates, silicate, phosphate, ammonia, trace metals (Delory, 2019^[12]); miniaturised in situ fluorometers for quantifying and monitoring harmful algal blooms (Wang et al., 2019^[13]).

Problems do remain, however. These include issues concerning integration, reliability and response time on autonomous platforms; few compact biogeochemical sensors can go deeper than 2 000 m; few sensors have multi-functionality and true multi-platform integration capability; and there is still a lack of integration of truly efficient commercial antifouling systems (Delory, 2019^[12]).

Biology and ecosystem

Over the last decade or so, one of the main advances in sensor technology has been the advent of multibeam and wideband (active) acoustic systems. Compared to single frequency, wideband capability has led to increased range resolution and better frequency spectrum data for species identification of fish and zoo plankton, detection of fish eggs & larvae, etc. (Fietzek, 2019^[15]). Multibeam systems have become more reliable and cost-efficient. Moreover, acoustic cameras have been emerging for fine scale studies of marine organisms in the last decade (Wang et al., 2019^[13]). On the passive acoustics front, compact, low power-consumption digital hydrophones are emerging, equipped with embedded bioacoustics processing (Delory, 2019^[12]; Delory, 2017^[16]).

Rapid advances in electro-optical technology have led to novel and better ways of detecting and imaging plankton in situ. Prototypes or commercially available high resolution imaging systems now allow plankton and particles to be detected across a wide range of sizes, up to the centimetre scale (Wang et al., 2019^[13]). Compact multiple-parameter optical sensors are now commercially available, able to identify up to at least seven phytoplankton groups; also available are miniaturised multi-channel algae sensing modules for detecting arising harmful algal blooms, as well as multifunctional optical fluorescence sensors with a 6 000 metre depth rating (Delory, 2019^[12]). Advances in laser measurement technology now facilitate 3D geo-referenced data collection in offshore surveys, and innovations in high-speed digital imaging are making for higher quality subsea images (Boyle, 2019^[17]). Notable are the advances being made in 3D with the help of photogrammetry (which defines the 3D reconstruction of an object or scene from a very large number of photographs taken from different points of view). Increasingly such innovations are paving the way for capturing in detail ecological processes and small changes in marine habitats which have been wrought by human activity in the ocean. Based on photogrammetry, recent developments in hardware and image processing make it possible to reconstruct high-resolution 3D models of relatively large areas (up to about one hectare), and it is expected that, as they become ever more efficient, they will allow coverage of increasingly large marine regions (Marre et al., 2019^[18]).

With the advent of artificial intelligence (AI), substantial progress is beginning to be made in the automatic processing and classification of species – a prerequisite for handling the huge quantities of video footage captured by cameras. In the case of benthic habitats, for example, automated classification is evolving rapidly thanks to advances in multi-spectral underwater image processing and segmentation algorithms as applied to coral and algal cover in reef systems (Bicknell et al., 2016^[19]); and new methodologies are emerging using genetic programming for content-based analysis in capturing the temporal dynamics of fish abundance (Marini et al., 2018^[20]). Deep Learning methods for underwater species detection and recognition are also developing rapidly, notably for fish (Salman et al., 2016^[21]; Naddaf-Sh, M., 2018^[22]; Villon et al., 2018^[23]; Wang et al., 2019^[24]; Ditria et al., 2020^[25]); and other marine creatures (Lopez-Vazquez et al., 2020^[26]), but also for more general object and marine resource recognition (Hu G. et al., 2018^[27]; Cao et al., 2016^[28]; Pelletier et al., 2018^[29]; Sun et al., 2018^[30]).

Virtual reality

Next-generation simulation and virtual reality technology is a further innovation that holds considerable potential for the future. Virtual reality technology is one that generates a high-fidelity simulation

environment by computer and uses a variety of sensor interfaces to enable the user to immerse in that environment. It is, in short, a visual platform integrating various different technologies (Xie, 2019^[31]). At industrial level, for example, digital twinning is attracting a lot of attention. A digital twin is the virtual representation of an asset (or process), used from early design through construction and operation, maintained and easily accessible throughout its lifecycle. It is finding its way into numerous marine activities ranging from shipbuilding and repair, predictive and preventive maintenance of vessels and offshore oil and gas structures, to aquaculture and offshore wind farms (Smogeli, 2019^[32]).

Virtual representation technologies are also emerging in the ocean science field, where the aim *inter alia* is to perform “high fidelity simulations of the ocean environment, visualization of massive and multidimensional marine data, and imitation of marine lives” (Chen et al., 2012^[33]). While they have yet to become mainstream in ocean science, they are being increasingly deployed as a tool for scientific exploration and discovery; Walcutt et al. (2019^[34]), Newell et al. (2017^[35]) and also Masse and Christophe (2016^[36]), for example, have used them to create realistic geovisualisations of coastal environments, while Masse and Christophe (2016^[37]) have deployed them for the geovisualisation of coastal tides. Chen et al. (2012^[33]) demonstrated they could establish a virtual sea-land integration platform capable of reproducing drifting- and diffusion- processes of oil spilling from sea bottom to surface. And more recently, Walcutt et al. (2019^[34]) used VR techniques to visualise a 50 km² ocean map by combining sensor data from a profiler sensor drifting freely through the water column, with its geolocated drift paths, and with corresponding satellite imagery.

Contaminants

Progress in recent years has seen an important extension of the parameters that can be measured and monitored by sensors, notably to heavy metals, microplastics, and toxins. Several projects on biosensors for toxins are underway or recently completed, notably in the EU. However, many are still at a low technological readiness level in terms of their integration on platforms (Delory, 2019^[12]).

Genetic sensors for microbes and eDNA

Molecular techniques have been advancing at a rapid pace, stimulating the search for genetic (or ecogenomic) sensors that might allow in situ analysis of genetic material. Genetic sensors offer a considerable enhancement of existing ocean monitoring instruments by providing autonomous, in situ capacity to detect and analyse DNA or RNA sequences in captured and sequestered organisms, thereby revealing useful information about their quantity and activity. In many cases, however, capturing and sequestering microbes, plankton and larger organisms is not possible. In such instances, their detection and genetic analysis can be performed through their environmental DNA or RNA as found in cellular material the organisms have shed. In situ, real time capacity is particularly pertinent to deep-sea observation for which, at least until recently, all eDNA surveys have been based on analyses of sediment samples processed on deck (Brandt et al., 2016^[7]).

Important advances in eDNA/RNA techniques are emerging (Regan, 2019^[38]; Mowlem, 2019^[39]), but as of 2019 the only highly advanced and commercially available ecogenomic sensor was to be found in the United States. The Environmental Sample Processor has been operating for some years, monitoring in real time a wide range of organisms in the water column, from fish (using eDNA signatures) and bacteria to invertebrates and harmful algae. Although such ecogenomic sensors have considerable cost-reduction potential in sampling operations, wider use of such instruments is currently unlikely because the initial set-up cost is very high (Wang et al., 2019^[13]).

Float arrays and fixed-point platforms – technological enhancement and extension of spatial coverage

At the latest count, there were just under 9 000 in situ platforms in operation world-wide in the seas and ocean (JCOMMOPS, 2020^[40]). They consist of, among others, float arrays (such as the ARGO system and the Global Surface Drifter Array), ocean gliders, ships of opportunity, animal borne sensors, tide gauges, moored buoys, but also cabled seafloor observatories and undersea cable array systems. They are crucial elements to learn about and monitor the marine environment, as well as to collect data for both weather and climate forecasts.

Advances in float arrays

Advances in sensor technologies go hand-in-hand with developments in fixed-point platforms (e.g. moorings, buoys, underwater cabled observatories, power cables) and in drifters and floats. In all these types of platform, the coming years are expected to see a broad swath of innovations come on stream.

Foremost among large-scale networks of floats is the Argo Programme, first implemented in 1999. The Argo Programme is a global array of around 3 500 to 4 000 active profiling floats, providing continuous observation of ocean temperature and salinity profiles from the surface down to a depth of 2 000 m, both in ice-free waters and, more recently, in seasonal ice zones (using ice avoidance algorithms) (JCOMMOPS, 2020^[40]). Moreover, improvements have seen pilot projects undertaken that have demonstrated Argo floats' ability to monitor biogeochemical parameters and to undertake measurements in the water column to depths of up to 6 000 m (Deep Argo) (Roemmich et al., 2019^[41]).

For the future, four innovation groups are foreseen. The first two will follow on from the pilot projects mentioned above, and will involve the deployment of biogeochemical sensors and deep-sea floats in various parts of the ocean (Deep and BGC Argo). A third and fourth will see the spatial expansion of the Core Argo array and a higher density of floats in some regions. All four improvements taken together form the "Argo2020 design", which aims to upgrade Argo to a genuinely global array for variables and scales.

Table 2 provides a summary of the additional floats and densification of coverage planned, the state of progress, and the ocean regions which are scheduled to benefit.

It is noticeable that for several items the requisite resources are not yet secured. Indeed, in recent years some key participating governments and national agencies have struggled with the financial burden of continuing to provide support for the Argo Programme (Weller et al., 2019^[42]). The economic consequences of the Covid-19 pandemic risk exacerbating the financial challenge.

Table 2. Summary of the Argo2020 design, including the required number of active floats and the present status of elements

Design element 2x indicates double density (i.e. two floats per 3° square)	Active floats	Status
Global – original	3 000	Implemented
Global – Antarctic	290	Pilot completed; implementation not resourced
Global – Arctic	70	Pilot underway
Global – Marginal Seas (2x)	220	Implemented where regional Global Ocean Observing System (GOOS) alliances are active
Global – Total	3 580	
Tropical enhancement (2x)	560	West Pacific implementation prioritised, but not resourced
Western Boundary Current enhancement (2x)	460	Kuroshio pilot completed. Final design still in development
Argo2020 Design	4600	

Note: The needed number of deployments per year is equal to the number of active floats divided by the mean float lifetime, presently about 4.2 years. The number of floats is inclusive of Core Argo, Deep Argo, and BGC Argo floats, forming a single integrated Argo Program. Source: Roemich et al. (2019^[41]).

Cabled observatories and undersea cable observation systems

Cabled observatories use power and data transmission cables to link up ocean sensors with on-shore facilities. This ensures continuous, high-frequency real time observation capabilities for monitoring the ocean from the seafloor, through the water column to the surface. Cabled observatory technology is often the most preferred option in coastal zones where the aim is to collect uninterrupted, sustained long-term high-resolution time series of ocean variables using high power-consumption devices such as video lights and sampling pumps, as well as instrumentation generating large volumes of data – such as scanning sonars, hydrophones, and high-definition video cameras (Juniper, 2018^[43]).

The number of cabled seafloor observatories has been growing over the last few decades, many of them being brought together into national or regional scale networks such as Ocean Networks Canada, the Japanese S-Net system (seismic), and the European Seas Observatory NETWORK (ESONET). ESONET currently comprises 12 observatories stretching from the Norwegian Sea to the NE Atlantic and the Mediterranean, all connected to land via cable or acoustic communication and designed to monitor physical, chemical and biological processes.

In recent years cabled ocean observation has had its capabilities greatly enhanced with the installation and operation of undersea cable arrays. These include single-node observatories such as the ALOHA Cabled Observatory as well as national and regional scale multiple-node systems such as the Japanese DONET Observatory (seismic and tsunami early warning) and the Canada/US OOI Regional Cabled Array (RCA). Much more recently, seafloor observatories serving both science and industry have come to fore – DELOS off the coast of Angola, and the Lofoten Verlag Observatory (LoVe) in Norway.

Over the next decades, improvements to the spatial (seafloor, water column and air-surface interface) and temporal (i.e. at time frequencies from seconds, to hours, months and even years) coverage as well as in the analytical capabilities of seafloor observatories might be expected to come from several sources - for example from the installation and operation of additional ocean observation systems.

There are however very few proposals for new cabled ocean observation systems, largely because they require substantial capital investment and high operational and maintenance outlays as well as international scale collaboration. To have traction, there has to be a convincing justification, for example the need to close major knowledge gaps on big issues of climate and the environment. One such gap

concerns the Arctic, for which proposals exist for the creation of a multidisciplinary, integrated Arctic Ocean observing system consisting of a trans-Arctic cable spanning the 10 000 kilometres from Norway to Japan. If built, it could provide the capacity for continuous real-time in-situ observations of the ocean interior under ice across a large portion of the Arctic. It is envisaged that the cable and its nodes would support activities such as vertical water column profilers, gliders, floats, AUV docking stations, long-range acoustic navigation and communication equipment. The cabled observation system would be powered by dual conductor cable run along the ocean floor and interspersed with land points (Baggeroer et al., 2018^[44]). While the various technologies for such an undertaking exist, the requirements for international collaboration, coordination, and synchronization of funding would be considerable.

Further enhancements to the performance of cabled observatories can be expected from a range of technological advances. For example, the addition of resident gliders, remotely operated and autonomous underwater vehicles supported by seafloor docking stations, the leveraging of observational and analytical capabilities through advances in various monitoring technologies, and their integration into multi-functional multi-disciplinary platforms (Berry, 2019^[45]) (see also next section).

Sensor-enabled telecommunication and power cables

A promising field of innovation is the placing of sensors on or within subsea structures so that the latter can also be used for collecting data on the marine environment. At least three types of cable are in principle suitable: ocean observatory cable arrays, and telecommunication and power cables for installations such as offshore wind and marine renewable energy sites.

As discussed above, cabled ocean observatories are already using modern fiber-optic cables (for power and high bandwidth) as part of their dedicated mission to gather data on complex ocean systems. New large-scale observations cable arrays such as the envisioned Arctic Observation system would clearly represent a significant extension of coverage.

New efforts are underway to make use of the world's future network of subsea telecommunications cables. The initiative is spearheaded by SMART (Science Monitoring And Reliable Telecommunications), and is conducted jointly by three United Nations agencies – International Telecommunication Union, World Meteorological Organization and the Intergovernmental Oceanographic Commission of UNESCO. The idea is to utilise the million kilometres of undersea telecom cables and the many thousands of repeaters as a platform for carrying ocean science sensors that, at least to begin with, would monitor temperature, pressure and seismic movement. The data gleaned in this way would perform a twofold service – help fill important data gaps in long-term measurements of the under-sampled ocean, and benefit global tsunami warning networks. With respect to pre-existing telecommunications cables, deploying scientific sensors in the deep ocean for the sustained gathering of ocean data that are otherwise difficult and expensive to obtain, is highly problematic. On the other hand, integrating sensors into new telecoms cables offers a promising, relatively inexpensive method of collecting important environmental data over long periods of time from deep-sea locations for which few other solutions exist (Howe et al., 2019^[46]).

Telecommunication companies operate and maintain worldwide about 420 subsea optical telecom cables covering a distance of around 1.1 million km – in the North Atlantic, North Pacific, the Mediterranean, the Indian Ocean, Oceania and so on (Hartog et al., 2018^[47]). The cables require periodical renewal and expansion, which offers the chance to integrate sensors during the production process. Indeed, it is estimated that most cables still to be installed could be fitted with sensors within the next 5 to 10 years. On the basis of a target of 2 000 SMART-enabled repeaters to achieve global coverage, and assuming an installation rate of 200 per annum (plus replacement repeaters after 10 years), the target could be reached in about 18 years (Howe et al., 2019^[46]).

However, the technical and other challenges are considerable. Reliability, for example, is key. SMART repeaters need to be designed in such a way as to ensure that scientific sensors and telecommunication

functions do not interfere with each other (Ota, 2019^[48]). Only some of the seismic monitoring instruments need to be installed within the repeater housing. Others, such as the pressure and temperature sensors, need to be positioned outside the housing – which means penetrating the housing to connect the instruments to the internal circuitry. It is also essential to isolate the sensors from the high voltage within the repeaters and to ensure that the normal functioning of the repeaters is not impaired by defects emanating from the external sensors. The tolerance thresholds set for subsea telecommunication cables are extremely high: the objective is typically to allow for no more than one internal failure per 25 years in 5,000 km of cable. Care would need to be taken that the introduction of sensor capabilities did not reduce that reliability threshold (Howe et al., 2019^[46]).

Cost is a further challenge. Estimates put the annual deployment costs at around 36 million USD as the instalment phase picks up speed, plus annual operating costs of around 10% of deployment costs (Howe et al., 2019^[46]). What remains unclear is who pays the incremental cost of adding sensors to cables that would be laid with or without the sensors attached. This could be government agencies, given the benefits to better understanding the climate and to improved tsunami early warning; and/or international development banks (such as ADB and IADB) given their interest in climate change, disaster prevention and mitigation, and greater connectivity. Industry might also be inclined to offer in-kind support in the form of engineering assistance, technical review, etc. (Ota, 2019^[48]).

Furthermore, there remain important legal issues. The proposed dual purpose cables combine telecommunication and marine data collection in a single cable. However, the two are governed by different legal regimes. Nonetheless, it is expected that as the project moves from development to deployment, progress will be made in refining the international legal status of the undertaking (Ota, 2019^[48]) (Howe et al., 2019^[46]).

Notwithstanding these challenges, demonstration projects are underway in Italian and New Caledonian waters, and further demonstration projects are planned for Portugal and Indonesia (Ota, 2019^[48]).

An alternative to SMART cable sensors are distributed optical fibre sensors (DOFS) which measure parameters such as temperature, vibration and static strain along the length of the sensing fibre and have been in use for several decades. They are increasingly accepted in industrial applications, for example to monitor strains on underwater power export cables and measure their exposure to subsea hazards (Van Hoestenbergh, 2019^[49]). They are also increasingly seen as a research tool, notably in environmental science. Future developments in DOFS point to possibilities to further harness the technology for oceanographic purposes. A growing number of studies indicate their potential for monitoring underwater geohazards such as sediment slides and current turbidity, and even long-term (i.e. annual to decadal) temperature changes in the deep ocean (Hartog et al., 2018^[47]). Their advantage is that they can be placed not only on telecommunications cables but also on other structures such as offshore wind farm power-export cables and inter-array cables. Recent studies have shown for example that DOFS on offshore wind export cables to detect and track ocean waves (Science Daily, 2019^[50]).

Hence the future expansion of the global undersea cable network, in addition to potential growth in connections to offshore arrays such as wind farms, offers tremendous opportunities to widen and improve coverage of scientific monitoring of the marine environment, not least in those areas hitherto poorly explored such as the deep sea.

Increasing autonomy in mobile platforms

Before delving into the progress that is being made in the evolution of autonomous underwater mobile platforms, it is worthwhile briefly distinguishing automatic systems and autonomous systems. Automatic systems can perform well-defined tasks without human intervention. Autonomous systems on the other hand: are designed to perform complex tasks under significant uncertainties in the system and when

operating in an unstructured environment; are highly dependable and must be able to handle external events and internal faults including reconfiguration, planning and re-planning; should be able to learn, adapt and improve; add extra layers between their measurements and actions which enable them to model and plan their actions, hence making deliberate choices (Sørensen, 2019^[51]).

Mobile platforms cover a wide range of vessel types, from Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) to Crawlers and Autonomous Surface Vehicles. Over the last two decades or so, ROVs and AUVs have been deployed increasingly in the ocean both for scientific and commercial purposes. They have been joined by a growing fleet of surface gliders, powered by solar and sail, cost-efficient underwater gliders (Barrera, 2019^[52]) and long-range auto-submarines, as well as by novel combinations such as Hybrid Remotely Operated Vehicles (HROVs) which can be used either as AUVs or ROVs, as the task in hand requires. Miniaturisation is also making its mark with the advent of small and micro-AUVs, which, growing in affordability and accessibility, are set to benefit broader user-groups such as schools, universities, and local communities. Swarms of small AUVs and combinations of different surface and subsea vehicles are also likely to become much more common as technological and scientific progress accelerates. In the field of mapping and monitoring, for example, Sørensen et al (2020) foresee a “quantum leap” in the efficiency of operating heterogeneous sensor-carrying platforms, estimating that already today mapping coverage may be 100 to 1000 times higher than the state-of-the-art technology just 6 years ago. Looking ahead, growing fleets of micro-satellites with customised payload sensors are expected to bring significant improvements to remote sensing and further contribute to the development of heterogeneous sensor-carrying platforms (Sørensen et al., 2020^[53]).

In the coming years, all the above vehicles will have an important role to play both in rendering activity in the ocean more financially and environmentally sustainable, and in enhancing our knowledge of ocean processes - including a better understanding of the past, present and future impact of economic activity in the ocean on marine ecosystems. As emphasised earlier, filling those knowledge gaps constitutes a huge challenge given the vastness, the diversity and sheer complexity of the ocean. To ensure that mobile platforms are capable of helping meet that challenge in ways commensurate with their potential, substantial progress will be required to enhance their autonomy.

Achieving greater autonomy will entail substantial improvements in numerous features, the most important of which are range, endurance, robustness, reliability, accuracy, and a spectrum of applications. More specifically, solutions will need to be found to a number of challenges outlined below.

Sustained presence at sea through improvements in power systems

Most of the current generation of Autonomous Underwater Vehicles require the presence of a mothership for launch and recovery, and for power supply and data uploading, tasks which may need to be repeated throughout deployment. Repeated interactions between an AUV and its mothership generate inefficiencies and increase the costs of an operation (the magnitude of which may be reduced if the mothership itself is replaced by an autonomous surface vessel – see later sections). This underscores yet further the need for much greater AUV autonomy. However, extending the operational lifetime of an AUV, building its capacity for very long-range missions in possibly very remote areas, and deploying it permanently on-site, places considerable demands on the vehicle’s power system. With the current generation of AUVs the biggest obstacle is limited battery performance in terms both of reliability (i.e. operating at considerable depths) and power consumption. Several different routes to improvement are being explored. They include: increasing the pressure resistance of batteries (e.g. installation of pressure tolerant gel encapsulation battery technology which can increase energy capacity by over half (Kraken Robotics Inc., 2018^[54]) using novel battery techniques such as chargeable lithium-polymer or semi-fuel cell, and replacing conventional lithium batteries with hydrogen fuel cells (Maslin, 2019^[55]) (Weydahl et al., 2020^[56]).

A further option consists in making use of external power sources. Ideally, this might involve tapping into a renewable ocean source such as wave energy. “Wave energy is still at a technology development stage where several different concepts are being progressed, as far as funding allows. Wave energy has not yet seen technology convergence or reached consensus on optimal design and optimal platform type, offshore, nearshore, surface or seabed mounted.” (Smart, 2018^[57]). There are indeed a few working examples of wave energy converters functioning successfully (Maslin, 2019^[58]; Cimino, 2017^[59]), among them projects demonstrating wireless power transfer for recharging AUVs (Whitt et al., 2020^[60]), but on the whole the technology requires further development (LiVecchi, 2019^[61]).

A nearer-term solution entails the use of a docking station for autonomous docking either on the seafloor or in the water column for recharging batteries, data transmission and communication purposes, and thereby extending the use and range of AUVs, ROVs and other vehicles. Demonstration projects currently underway show there is a range of different options.

The idea of Subsea Docking Systems (SDS) has grown out of the oil and gas industry’s need to cut operating costs and expand the opportunities for operations even in poor weather conditions, by using permanently resident ROVs/AUVs. The growing global offshore wind industry has also warmed to the use of ROVs and AUVs for inspection and maintenance, and the cost advantages of permanently deployed vehicles real-time and weather independent. Hence, the concept of a resident ROV, AUV or HROV is relatively recent, and projects underway are at different stages of development and technology readiness. For power supply, some of the projects are using submerged battery packs on the seafloor which can be scaled up or down depending on the requirements of the task in hand, while others use a power source located on a floating platform. The use of hybrid vehicles has considerable advantages. While operating in ROV mode, they can unplug themselves, then operate in AUV and move autonomously to another SDS (Trsllic et al., 2020^[62]).

The concept has garnered considerable commercial interest and investment. But to be fully operable in ocean conditions distant from shore, the vehicles will need to acquire greater autonomy - high levels of automation with the help of on-board sensors, high-quality computer vision, and advanced control and navigation approaches, all reliant on AI. This is especially important for the underwater docking procedure. Recent demonstration projects have shown that autonomous docking to static subsea docking stations is indeed possible (Maslin, 2019^[63]; The Maritime Executive, 2019^[64]), as is docking to dynamic docking stations in real-life ocean conditions (Trsllic et al., 2020^[62]). In addition, unmanned surface vehicles (USVs) are under development to support autonomous underwater vehicles by providing battery recharging in the water column, thereby removing the necessity for manned vessels and frequent launch and recovery (Maslin, 2019^[55]).

Navigation

For the most part, the current generations of AUVs have only limited autonomy and conduct pre-planned missions due to limitations surrounding autonomous navigation. Such AUVs depend on the availability of accurate maps of the seafloor and underwater obstacles, and on keeping within range of networks of acoustic transponders to steer the right route. Path planning in known environments involves seeking out feasible paths and optimising the route to be taken. Missions in unexplored or partially unknown waters necessitate much more AUV autonomy, and the use of more sophisticated algorithms that can respond rapidly to dynamic environments.

Various algorithms are under development which have shown themselves to be effective in detecting objects (through for example a multi-beam forward looking sonar) and producing those objects’ profiles (Yan et al., 2018^[65]; Li et al., 2018^[66]). AI is progressing in other fields of marine autonomy, for example in

the development of decisional algorithms able to weigh up the balance of risks and benefits of certain manoeuvres (Safety4Sea, 2019^[67]).

Three dimensional mapping of the seabed

A further area where technological progress is required if subsea autonomy is to be significantly advanced is 3D mapping of the seafloor for scientific and commercial applications, conducted with AUVs (rather than with ROVs, as has until now been the case). The difficulty with using current state-of-the-art AUVs has been the inability to get the AUVs to navigate sufficiently close to three dimensional objects in order to obtain useable optical imagery. Demonstration projects on algorithmic motion planning however are beginning to yield results (Zereik et al., 2018^[68]). Most have involved the deployment of single AUVs (Hernández et al., 2016^[69]). However there is also growing interest in trajectory-planning algorithms for deploying entire teams of AUVs in three-dimensional seafloor mapping (Salavasidis et al., 2018^[70]).

Network system approaches and underwater data exchange

Similarly, there is growing interest in solving the problems encountered with developing network systems for co-operative motion planning, navigation and control more generally. These systems are required to enable groups of inter-communicating robotic vehicles to work together to inspect, survey, and map challenging marine environments. This is a highly active area of current research and numerous different projects are working on the development of suitable algorithms and the practicalities of implementation (Zereik et al., 2018^[68]; Offshorewind.biz, 2018^[71]).

A recent example of a successful trial is the GLIDER project that involves three ocean autonomous and mobile platforms: a Sea Glider, a Sailbuoy and a Wave Glider (Box 2). However, there is still a long way to go before teams of subsea marine vehicles that are capable of autonomous survival in the ocean become common place. Challenges remain in respect of a host of issues: decisional autonomy; the ability to draw energy from the surrounding environment; cognitive ability permitting adaptation to changes in the conditions and mission objectives; and the capacity to perform assignments efficiently and effectively (Zereik et al., 2018^[68]).

An important part of such autonomy is the development of technologies that allow ASVs, AUVs and ROVs to exchange data among themselves. This will require simultaneous use of underwater acoustic channels and optical channels, together with strategies to optimise both the subsea communications network and the configuration of the vehicle fleet, all in real time. Technologies are now coming on stream which will provide crucial building blocks for such innovations. These include new types of optical modems for short-range communications, high-precision high-performance acoustic modems and positioning devices fitted with atomic clocks (Zereik et al., 2018^[68]; Petrioli, 2019^[72]; Boone, 2019^[73]; Kebkal et al., 2019^[74]).

Box 2. Networked system trials: The GLIDER project

The glider platforms are equipped with a suite of sensors to collect chemical, physical and biological data from the ocean, and complemented by a data management platform to enable high integration of the collected data. The GLIDER project was implemented in 2018 over a 6-month period in the Lofoten area along the Norwegian coast, the aim being to improve knowledge of the ecosystem during the spawning period of the Atlantic cod, and provide new insights into the dynamic and timing of biological events. Moreover, data from the survey are currently being processed which will deepen understanding of the surveyed ecosystem across a wide spectrum of natural phenomena – from primary production to

zooplankton, fish larvae, adult fish and mammals. Finally, the project has also benefitted weather forecasting by being able to assimilate data in real time into oceanographic models (Camus, 2020^[75]).

In light of such rapid progress in so many fields of marine technology research, in parallel with on-going advances in sectors such as automobiles, mobile telephony and processors, some experts foresee that true autonomy in autonomous ocean observations is in reach within a decade from now (Whitt et al., 2020^[60]).

Systems integration in ocean observation: scaling up for the future

A striking trend of recent years in ocean observation is the growing recognition of the importance of connecting up systems and networks with the aim to share costs more broadly, expand coverage, exploit potential efficiencies of scale or increase synergies. Opportunities range from the integration of similar or diverse equipment, technologies, instruments and infrastructure at observatory level, to pulling together entire networks of ocean observation systems at regional and ocean-basin level.

From local-scale observation systems...

Visions of how seafloor cabled observatories should and could look in the coming decade have been firming up recently, as the performance of current ocean observation technologies becomes increasingly sophisticated and powerful, and new technologies emerge. These observatories have been highly successful in deploying platforms fitted with a rich array of visual image systems as well as marine sensors, and demonstrating the benefits of power and communication cables. This is making it possible to conduct remote monitoring of the deep-sea on a frequent and continuous basis, and over long periods of time. The principal drawback of cabled seafloor observatories is their limited spatial coverage, since they are fixed. One way around this limitation has been the introduction of networks of sea-bed observation nodes, as developed by the Ocean Network Canada, the Deep-ocean Environmental Long-term Observatory System (DELOS) off the coast of Angola, and so on. It is envisaged that this concept could be carried further in future with the creation of multiple co-ordinated observation clusters, established at suitable intervals along the seafloor. This would allow cabled deep-sea observation to move from the monitoring of local habitats to the tracking of species' movements into and through neighbouring environments, thereby building a much more complete picture of deep-sea ecosystems than was hitherto possible (Aguzzi et al., 2019^[76]).

Even so, data gaps would persist at spatial scale - locally, regionally and basin-wide – as well as within the water column. To help close many of those gaps, the idea is gaining ground to increase spatial and water-column coverage of observation capabilities by adding permanent mobile platforms to sea-floor observatories' infrastructure. Such mobile platforms range from benthic crawlers and AUVs to both tethered and untethered ROVs. Together they enable an extensive range of tasks to be performed, e.g.: mapping the distribution of benthic habitats and biota as well as frequent monitoring of the water column at different depth scales (AUVs and ROVs); video-data collection and management and maintenance tasks within the observatory infrastructure, including fouling of structures and their colonisation by fauna (ROVs); conducting census observations at specific locations and over extended periods of time (Crawlers). Underwater docking facilities would provide for recharging, communication and data transmission.

As previous sections in this report have shown, innovation in each of these mobile platform technologies is advancing rapidly and all are operational, albeit at different levels of maturity. Integrating them into a coherent, effective and reliable cabled sea-floor observatory system, however, has yet to attain full operational readiness, and will require continuing efforts over the coming decade (Aguzzi et al., 2019^[76]; Aguzzi, 2019^[77]).

...to national-scale observation systems...

Many countries do not yet have an integrated national ocean observation system, but there is growing recognition of the benefits that national integration can bestow upon a country's capacity to address the many ocean-related challenges of the future. Some countries that already have nationally integrated systems are serving as useful examples for others, notably the U.S. Integrated Ocean Observing System (U.S. IOOS) and Australia's Integrated Marine Observing System (IMOS). Both systems were built by incorporating and scaling-up existing ocean observing capabilities (Stewart et al., 2019^[78]). Canada is among those countries seeking to develop a national vision and strategy for coordinated ocean observation, so as to reduce or eliminate duplication and gaps in its highly diverse observation activities and multitude of observation platforms, and maximise the benefits they could potentially generate throughout the value chain – from data production through to end-use. The Canadian Integrated Ocean Observation System (CIOOS) currently under development brings together and leverages existing Canadian and international ocean observation data into a federated data system. A CIOOS test-phase is underway (Stewart et al., 2019^[78]).

Similarly, New Zealand is working towards an integrated national ocean observation system – NZ-OOS. While cognizant of the changing climate and the impacts on the ocean, no coherent national plan currently exists that meets the needs of the various stakeholder communities affected (scientists, business, local populations, etc.). Moreover, ocean observing in New Zealand has historically suffered from limited investment. The aim is to leverage existing ocean observation capabilities with a view to optimizing both effort and resources flowing into the system (O'Callaghan et al., 2019^[79]).

...to large-regional-scale observation systems...

Integration of observation infrastructures in coastal ocean observation appears to be moving to the regional scale, motivated not least by the extent of the environmental threats to coastal waters stemming from human activity and requiring continual monitoring. Europe is a case in point, and the JERICO-RI project a pertinent illustration of this trend.

JERICO (Joint European Research Infrastructure of Coastal Observatories) is a series of EU-funded projects launched in 2011 and currently involving 17 EU countries and 39 partners. In 2020 it entered its third phase: JERICO-S3. The principal objective is to construct a pan-European sustainable Research Infrastructure – the JERICO-RI – that uses an ecosystem approach to monitor marine coastal and shelf dynamics and the marine coastal environment, and provide timely, continuous and high-quality environmental data (physical, biogeochemical and biological) (JericoNext, 2020^[80]; Delaunay, 2019^[81]). The urgent need for such high-quality data was recently underscored by a survey of European scientists and marine monitoring authorities which found that the most commonly identified threats to the marine environment were marine litter, shipping, contaminants, organic enrichment, and fishing, and that among the main impacts of those threats identified by the majority of survey respondents, habitat loss, habitat destruction, underwater noise, and contamination figured prominently. Yet, most respondents considered current monitoring of threats to be only partially adequate or not adequate, notably with respect to the spatial and/or temporal scales at which monitoring takes place, and inadequate monitoring of certain parameters (Painting et al., 2020^[82]).

The basic components of the networks of national multi-platform coastal observations that JERICO-RI provides, include a wide range of nationally funded observing platforms, such as FerryBoxes, fixed platforms (moorings, pilings), underwater gliders, high-frequency (HF) radar, profilers and vessels of opportunity. A key finding of the JERICO-RI project to date has been that monitoring of coastal systems and processes at the relevant spatial and temporal scales points strongly to the need for an integrated multidisciplinary and interoperable coastal observation system of systems. Integration into such a system of systems has begun (Farcy et al., 2019^[83]). Next steps foreseen in the planning through to 2027 include

inter alia a study to design the place of JERICO-RI as the coastal component of EOOS, and the preparation of a (at this stage still hypothetical) Implementation Phase (JericoNext, 2020_[80]).

...to ocean-basin scale observation systems

In light of the growing recognition of the vital role played by the ocean and seas in the global climate system and biosphere, and the crucial resources they provide, a strong case is being made to develop and implement longer-term visions for organising observation systems at ocean-basin scale. Illustrative examples are the proposed creation of a sustained Arctic Ocean observing system (ARCGOOS), the concept of the All-Atlantic Ocean Observing System (AtlantOS) programme, and the enhancement of the existing Indian Ocean Observing System.

The Arctic presents distinct needs and challenges which require novel strategies for ocean observation. The proposed development of an Arctic Region Component of the Global Ocean Observing System (ARCGOOS) would constitute a transformative approach entailing the integration of physical and biological marine sciences, engineering, computational, social and behavioural sciences, and other knowledge systems. At this scale, convergence has not so far been achieved anywhere. It is thought, however, that it could be feasible for the Arctic, since linkages among different disciplines, sectors and knowledge systems are arguably closer than elsewhere. Moreover, in practice, establishing a sustained ARCGOOS would mean adapting and integrating existing observing activities together with the development of new systems specifically designed to meet identified ARCGOOS needs (Lee et al., 2019_[84]).

Efforts at ocean-basin scale would need to focus inter alia on integrating remote sensing and in-situ observations. Comprehensive observations covering the spatial and temporal dimensions of a rapidly changing Arctic environment are as yet not available, not least because currently available sensor technologies for biology, biogeochemistry and atmosphere are in need of greater improvement. But advances in the deployment of multipurpose autonomous observing platforms and infrastructure are also needed, especially low-cost, long-endurance autonomous platforms for large-scale, sustained observing, fitted with small, low-power sensors - ice-based instruments, surface drifters, profiling floats, underwater gliders and autonomous surface vessels. To be fully operational underwater, autonomous observing systems would require geopositioning and telemetry, also still undergoing development (Lee et al., 2019_[84]).

The AtlantOS programme is a forward-looking framework and basin-scale partnership to establish a comprehensive ocean observing system for the Atlantic Ocean as a whole by 2030 (AtlantOs, 2020_[85]). Basin-scale ocean observation in the Atlantic Ocean has to date been organised around loosely-aligned arrangements to connect up national and international efforts. However, such arrangements tend to suffer from numerous drawbacks. Monitoring activities performed in the national Exclusive Economic Zone (EEZ) do not connect systematically with international networks, tend to be targeted to local and national needs, and managed at the national level. Moreover, observation networks tend to be focussed on specific themes and issues, and to work independently. In addition, there is often too much focus on physical ocean EOVS rather than on biogeochemical, biological and ecosystem variables (deYoung et al., 2019_[86]).

The aim of AtlantOS is to build on the work of the two international bodies co-ordinating global ocean observation operations (i.e. the Global Ocean Observing System and the Group on Earth Observation) with a view to facilitating ocean observation on an Atlantic Ocean Basin scale. To that end, it brings the various observing communities, countries, partners and stakeholders from around the basin closer together to improve and streamline the use of ocean observations in delivering public services and sustained economic benefits to the many users of ocean observation data.

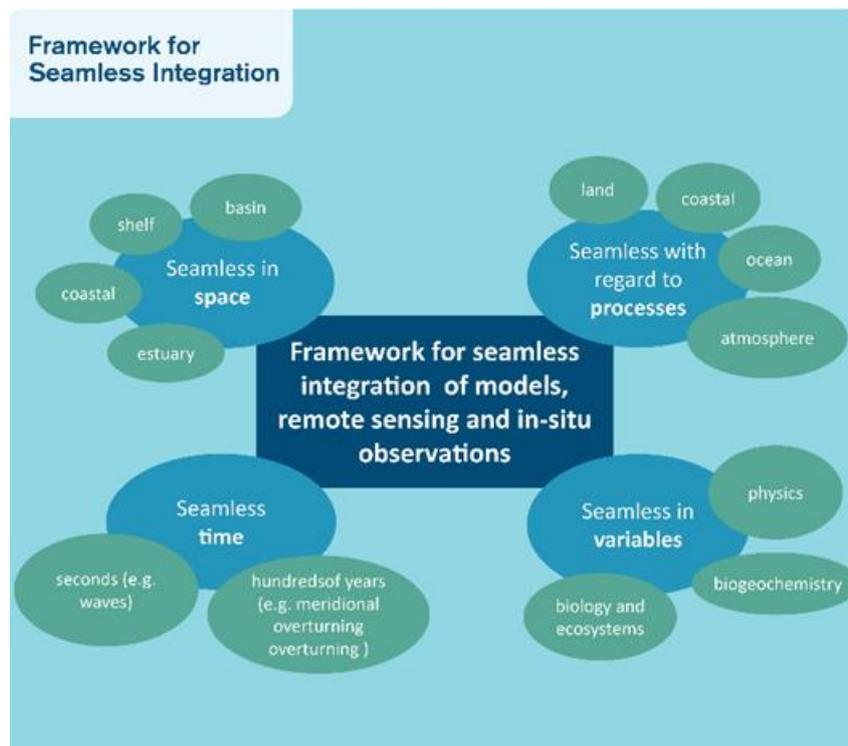
The AtlantOS proposal places great emphasis on the governance and management dimensions of basin-wide ocean observation. However, the system will necessarily also involve a high degree of operational

co-ordination of the many ocean observation platforms and infrastructures involved – from sea-floor facilities, moorings and floats to surface gliders, AUVs, drones, and satellites for navigation, communication and remote sensing. In terms of cyberinfrastructure, the basin-scale approach will demand seamless integration for the task at hand (see Figure 1) – seamless in spatial terms (continental shelf, coastal and estuary); in temporal terms (from seconds to decades); in process terms (land, coastal, ocean, atmosphere); and in terms of Essential Ocean Variables (physics, biogeochemistry, biology and ecosystems) (deYoung et al., 2019^[86]).

The Indian Ocean Observing System, IndOOS, a sustained basin-scale observing system, is a major source of Indian Ocean data. It comprises five in situ observing networks which need to be co-ordinated: moorings (RAMA), profiling floats (Argo program), surface drifters (Global Drifter Program, GDP), repeat temperature lines (XBT network), and tide gauges. The networks are supplemented by remotely sensed observations of surface winds, sea level, etc. Recommendations for the next decade include enhancements of sensor capacity for biogeochemical measurements as well as new sensor technologies, and the addition of new autonomous and expendable platforms (Hermes et al., 2019^[87]).

Specific requirements concern a doubling of Argo floats close to the equator; a substantial expansion of Deep Argo (the Indian Ocean currently has 14 north of 40°S, whereas at least 250 floats are considered necessary); enhancement of surface drifters with barometric sensors (for weather and seasonal forecasts); expansion of The Global Sea Level Observing System (GLOSS) network; and increased satellite missions for remote sensing (Hermes et al., 2019^[87]). Such enhancements will require considerable further efforts in platform system integration and co-ordination.

Figure 1. Content of a framework for the seamless integration of models, remote sensing (satellites) and in situ (in-water) observations



Source: deYoung et al. (2019^[86]).

3 Steps required to sustain the current innovation momentum in the digital ocean economy into the future

The previous sections provided an overview of some of the key advances in digital innovation in ocean observations which are in the pipeline or likely to come on stream in the coming decade. Combining all of these into a functioning and effective digital system of ocean data collection, analysis and action holds great promise for the medium- and longer-term future of the ocean economy. But many of those innovations described will not come to fruition or find widespread use entirely of their own accord. They will require strong supportive, organisational and collaborative action in a wide range of areas. These areas are detailed in the following sections and include

3.1. Cost reduction and scaling up of production volumes

A key concern of ocean technology developers is how to achieve market-driven demand for promising technological developments so that innovations may benefit from being manufactured at scale. Perhaps the most obvious path towards scale production of ocean innovations is through industry. At present, there are certainly markets for traditional industrial applications of sensors and numerous other digital technologies. These are typically destined for the monitoring of offshore infrastructures and operations, the delivery of environmental impact assessments, and the monitoring of water quality in inland and coastal waters. Advances in digital ocean technologies that can be proven to quickly reduce costs for industry have also been marketed successfully, although there is a widespread perception that markets remain small relative to their potential, and there is limited appetite for adopting state-of-the-art technologies among industry players. However, ocean observation systems as portrayed in the previous section offer an underexploited but powerful suite of tools for providing solutions to problems faced by industry, ensuring the sustainable use of marine resources and understanding the ocean more broadly.

Hence the search is on for ways to leverage the opportunities offered by ocean industry activities, in order to exploit existing markets more effectively, make inroads into new markets, generate more cost-efficient solutions, and consequently scale up production. Multiple approaches may contribute to achieving such an outcome, e.g. new business models and new forms of collaboration between ocean science and industry; improving ocean literacy among political and financial stakeholders; identifying and nurturing new communities of users; greater standardisation of ocean technology products and processes. They are detailed below.

New markets, new actors and new business models for ocean observing systems

Pulling together the trends outlined in the previous sections suggests that the coming decade is very likely to witness a gear change in the global effort to accelerate and expand ocean observation and research, provided of course that the economic and financial reverberations from the Covid-19 pandemic do not seriously derail that global effort.

The potential gear change is being driven by developments on two fronts. First, substantial progress is being made in the instrumentation and platforms that will be required to perform ocean observation and research on the scale required. Second, there are many strikingly ambitious visions for integrating networks and systems of ocean observation, data gathering and data analysis at all spatial scales – local, national, regional and global – which, even if only partially realised in the next 10 to 15 years, should provide huge stimulus to the deployment of current and next-generation ocean technologies. They in turn will generate a flood of ocean data which will be of great value to science, but also potentially to society and the economy.

However, data alone are unlikely to produce many such socio-economic benefits. Rather, they will need processing, packaging and delivering as information and services which are useful to users in all relevant domains. Hence, the anticipated ocean data explosion should present a fertile breeding ground for specialists in data processing to exploit. Their success will depend to an important extent on advances in two areas. The first of these concerns the need to understand - in much more detail than is presently the case - the ocean data value chain as it evolves through time. That is essential for gaining a better understanding of its various actual and potential users, their interests, and the market opportunities and social benefits associated with their activities. The second follows from the first and concerns the need to develop new business models in order to adapt to the new dynamically changing ocean data context. Designing business models for better packaging of ocean data is still very much in its infancy compared to other sectors. Looking over to other sectors for valuable experience and guidance – e.g. the use of remote sensing in the agricultural sector – could therefore prove a useful avenue to explore. In effect, creating and diffusing more value and more socio-economic benefits from ocean data is key to sustaining the much hoped for expansion of ocean science and research in the coming decade and beyond.

New forms of collaboration in ocean technology development for better market alignment

New forms of collaboration between ocean science, technology developers, business and industry, academe and other stakeholders, are being sought to better align advances made by science with prospective markets, and to bolster innovation capacity in all sectors. Various avenues are being explored or at least proposed, which point to new directions in this respect.

As earlier OECD work (OECD, 2016^[1]) has indicated, the innovation landscape in the ocean economy is undergoing considerable change, not least with the emergence of ocean economy knowledge and innovation networks. These are initiatives that aim to bring together a diverse range of players – from public research institutes, universities and relevant public agencies to large companies and SMEs – to combine research efforts on all kinds of different aspects of the ocean economy (marine robotics, aquaculture, marine renewable energy, biotechnologies, and so on). Documented benefits from many such innovation networks include, among others: greater coherence and co-ordination of approaches across disparate research communities to leverage cross-sectoral synergies; a rich diversity of skills and disciplines to address the scientific, technological and logistical complexities of modern-day research; and positive spill-over effects benefiting society more generally.

Similarly, it is argued that a paradigm shift is required that makes for more systematic engagement of users and user communities. Instead of the ocean observing community first generating data, analysing it to

produce research and subsequently stimulating interest in results among users, there is a need to engage users much earlier in the process through the likes for example of surveys, questionnaires and stakeholder meetings (Buck et al., 2019^[10]).

A recent illustration of this new approach is to be found in the field of biogeochemical sensing in ocean observation systems. The AtlantOs EU H2020 project contacted developers of biogeochemical sensor and instrumentation technology around the world to request their help in roadmapping (i.e. providing technical features, development timetable, expected TRLs, etc.) the availability of instruments over the coming decade. The aim was to enable both technology developers and ocean observers to foresee and plan for the timely use and uptake of the newly emerging innovations. While there are concerns around disclosure of intellectual property and strategic development plans, there is also evidence of substantial benefits for technology observers in the shape for example of attracting at an early stage the interest of the observing community in their products, and providing them with links to platform and observing systems (Wang et al., 2019^[24]). A further example is the proposal put forward in the United States to overcome the currently fragmented operation of ocean-related organisations by creating an Ocean Partnership for Sustained Observing (OPSO). The objective is to increase engagement and coordination of the ocean observation science community with foundations and philanthropic organizations, NGOs, academia, US federal agencies, and the business sector, on the basis of their shared interests in observational data and related products (Weller et al., 2019^[42]).

Improving ocean literacy for accessing risk capital

Lack of ocean literacy among financial and political stakeholders has been identified as a key factor hampering the adequate funding of many ocean economy innovation projects, both in Europe and in North America. In practice, poor levels of ocean literacy derive from a lack of awareness of the challenges of operating in an ocean environment, and in particular a lack of understanding of, and capacity to assess both the potential benefits and the risks associated with such projects. That, in turn, appears to be linked to the fact that, compared to land-based projects, would-be ocean business stakeholders have very few concrete case studies on which to base their assessment of the capacity to assess opportunities and risks. Ocean economy technology developers are aware of this gap and many innovation network centres are working towards bridging it. But ultimately, improving ocean literacy goes beyond the business dimension. It is a task for schools, universities, political stakeholders and civil society more generally, and warrants more effort at all these levels as the UN Decade of Ocean Science for Sustainable Development approaches.

Greater standardisation of technology processes and products to reduce costs

Across the entire ocean technology spectrum – from offshore oil and gas, shipbuilding and subsea cabling to offshore wind and shipping – standardisation of processes and products plays, and will continue to play, an important role in cost reduction. Similarly with sensors and sensing platforms, their limited availability and high cost have considerably hampered their wider deployment for ocean observation purposes. Recognition of the problem has led to greater research efforts in recent years to improve the pipeline of low-cost instruments not least through standardisation of component parts and work flows.

An illustrative example is the EU funded SenseOCEAN project. It was set up to develop new chemical sensors for monitoring the marine environment which could be pulled together into an integrated multifunctional sensor package to conduct for instance combined water chemistry studies. The result was a suite of novel instruments ranging from electrochemical microsensors and autonomous nutrient in situ sensors to multiparameter optical sensors and lab-on-chip innovations. Sensor operations were harmonised to ensure functionality with common interfaces, plugs and connectors, and all sensors are

useable on a variety of frames and gliders. Moreover, the data formats were also standardised enabling the data processing and dissemination to be automated, achieving further cost savings. The sensors are low-cost and can be mass produced (SenseOcean, 2017^[88]). Similarly, among the benefits of a range of sensor innovations demonstrated by the NEXOS project was that standardisation of products and procedures can lower costs by reducing the complexity of observing operations, improving reliability and cutting down on labour inputs (Delory, 2017^[16]). Both projects underscore the vast scope still available for further standardisation in the field of ocean observation.

Identifying and nurturing new communities of users

A further avenue for achieving higher production volumes of sensors and other ocean observing instruments is to step up the engagement of users at all possible levels. In this regard, increasing attention is being devoted to the notion of citizen science, i.e. encouraging the general public to collect and analyse marine-related data, typically as part of a collaborative effort with professional scientists. As technology progresses and more lower-cost sensors (e.g. for biogeochemistry and biology) and sensor platforms become available, ever more opportunities will arise to enhance professionals' coverage and resolution of data collection through contributions from citizen scientists, stakeholders and the public. Especially coastal environment observation is likely to benefit from such widespread participation. Potential candidates for recruitment to the cause include for example sailing boats and small recreational fishing vessels, and public/private coastal infrastructures like piers and harbours, but also institutions and community entities such as schools, universities and local authorities. With the help of mobile applications and social media, the wider involvement of interested individuals and groups in data collection and dissemination could be harnessed to build more public engagement in marine science research (Wang et al., 2019^[24]).

However, data quality is of the essence in ocean science, and steps would be required to ensure the integrity of data collections. The upcoming UN Decade of Ocean Science offers an excellent opportunity for public authorities to leverage citizen science engagement in a more structured fashion, while offering guidance on data quality control, best practices, and collaboration with professional scientists.

1.2. Industry-science collaboration to extend ocean observation coverage

Collaboration between science and industry in capturing marine data is established in areas such as the maritime transport and offshore oil and gas industries. However, building the kind of global deep-ocean observing system that is fit for purpose in addressing the challenges of the coming decades will require deeper and more widespread collaboration than is currently the case. Industry-science cooperation tends to be short-term rather than sustained and long-term, albeit with some notable exceptions; and while there are many good examples of collaboration at local and regional level, there are few operating at ocean-basin and global level. Yet, there are abundant opportunities for new and expanded synergies among the growing number of industries, individual businesses and other commercial organisations involved in deep-ocean observing (Levin et al., 2019^[14]).

Oil and gas industry

Ocean science collaboration with the oil and gas industry is not only well established but also well developed. Indeed, the mutual benefits from such joined-up efforts are considerable, ranging from improvements in survey techniques and observation and monitoring, as well as in spatial and temporal observation coverage, to enhanced data value and lower costs for operators.

Throughout the various phases of the life cycle of a typical oil and gas project, there are multiple opportunities for synergies arising from collaboration between industry and ocean science (see Table 3).

Table 3. Scientific use of data from typical industry remotely operated vehicle operations in offshore oil and gas activities

Oil and gas lifecycle stage	Typical deep-water mission of industry ROV	Potential scientific use
Exploration	Short surveys (visual and sonar) to look for potential hazards to infrastructure and operations Also to ensure seabed left “as found” after decommissioning	Opportunistic observations of species, ground truth/point data on habitats and common species (e.g. for baseline pre-impact assessment) Quantification of impact of well on seabed.
Development	Environmental survey to check for potential sensitive habitats or species, using video or still images Perform or monitor some aspect of subsea construction work	Quantitative ecological assessment of benthic megafauna
Operation	Regular or frequent inspection of pieces of subsea equipment (video and high resolution stills) Jacket inspection and survey of marine growth on structures Pipeline inspection/integrity survey Riser inspection/integrity survey	Opportunistic observations of megafauna, with possibility for growth-rate studies Quantitative ecological assessment of organisms growing on hard substrates Qualitative data on mid-water fauna
All stages	Seabed sediment sampling	Analysis of sediment properties
Decommissioning and recovery	Recovery of riser and/or subsea infrastructure	Confirmation of video identification of biomass, of growth-rate studies, and re-colonisation studies

Source: Condensed version of Table 2 in Macreadie et al. (2018_[89])

In terms of short-term collaborative projects, Levin et al. (2019_[14]) point to numerous examples from the last decade which have addressed a wide spectrum of issues: extent of and recovery from anthropogenic impacts; local biodiversity; impacts on reef-forming corals; and fish habitats associated with pipeline infrastructures. There are however far fewer examples of long-term collaborations, although three industry projects perhaps stand out as successful partnerships. These are: the two Deep-ocean Environmental Long-term Observatory System (DELOS) observatories; the Lofoten-Vesteralen (LoVe) observatory; and Shell’s Stones Deep Water Project.

DELOS operates on the seabed in a deep-water (1 400 m) oil field on the Angola Margin, with one observatory right next to subsea infrastructure and the other 16 km away. They conduct long-term monitoring through a series of scientific joint activities, making the data publicly accessible. LoVe is a cabled seafloor observatory on the deep Norwegian Shelf with a particular focus on reef-forming corals. The data generated by the observatory are publicly available in real time (the environmental data gathered in the course of oil and gas activities being usually not considered commercially sensitive). Shell’s Stones Deep-Water Project is a joint initiative with two universities, the Fugro company, and NOAA. It makes use of the oil and gas infrastructure to collect long-term deep-water data for ocean observing (Weller et al., 2019_[42]; Levin et al., 2019_[14]).

All the above examples are of a local or regional dimension. Examples of global level industry-science initiatives are harder to find. Such initiatives with global reach can, however, be highly effective, as

demonstrated by SERPENT, the Scientific and Environmental ROV Partnership using Existing iNdustry Technology. SERPENT works by gaining access to unused ROV capacity to collect deep-ocean data with added value. As of 2018, the project had conducted more than 125 deep-water missions in Europe, North and South America, Africa and Australia, resulting in over 50 peer-reviewed scientific papers (Levin et al., 2019^[14]).

Hence, a strong case can be made for scaling up the level of deep-ocean coverage through collaborative ventures with oil and gas operations in all relevant ocean basins of the world. This might be achieved for example by installing deep-water observation nodes at all regional centres of oil and gas activity (Levin et al., 2019^[14]). The mutual benefits could be considerable, though not without resolving numerous issues that might impede the creation of such initiatives. Solutions can in many cases be found. Table 4 offers an overview of some of the mutual benefits, obstacles, and examples of possible solutions.

Table 4. Science-industry collaboration on deep-sea industry remotely operated vehicle operations: A win-win future?

Benefits to science	Benefits to industry	Roadblock	Potential solution
Acquisition of valuable data for science on: Organism distribution, behaviour, interactions, population dynamics, community ecology, ecosystem structure & functioning	<p>Greater understanding of operational environment and Impacts</p> <p>Improved knowledge (including for contractors, regulators and other key stakeholders) of life and habitats around deep-sea structures to meet regulatory and other requirements</p>	<p>Industry time-constraint to collate, catalogue & provide data/imagery to scientific organisations and individuals</p> <p>Additional work scope and/or equipment to ROV operation requiring extra offshore scientific support and causing concerns about insurance, health and safety, confidentiality etc.</p> <p>Possible revealing of violations of industry standards or legal frameworks</p> <p>Lack of understanding of basic data collection principles by pilots or operators of industry ROVs</p>	<p>Draw on experience from existing long-term science-industry collaborations, e.g. SERPENT, to build trust and confidence</p> <p>Collaboration to provide robust scientific knowledge to support higher quality, less costly environmental surveys</p> <p>Collaboration to better understand marine growth on structures and develop anti-fouling solutions, to help industry meet regulatory requirements</p> <p>Apply and/or adapt training protocols and training packs on recording behavioural observations, capturing samples, habitat mapping etc. and build into future ROV pilot training modules</p>

Source: Author compilation based on Macreadie et al. (2018^[89]).

Submarine cables

Expanding the use of sensors could be substantially made by integrating them into telecommunications cables, power cables serving offshore wind farms, and mooring cables. Alone the global subsea communications network of over 1 million km offers vast opportunities for installing more sensors, given that parts of the network require frequent renewal and replacement.

Similarly, the anticipated rapid expansion of offshore wind energy in the coming decades (both fixed and floating) suggests a growing range of possibilities to widen sensor coverage underwater. However, this will

require close collaboration between the ocean observing community and the industries, regulators and other stakeholders concerned in order to resolve a number of important technical and legal issues.

Vessels of opportunity

There are numerous examples of commercial vessels that have been used as vessels of opportunity for many years now. They include container ships, cruise ships, ferries and fishing vessels, and recently racing yachts (e.g. Volvo Ocean race, Vendee Globe). In many cases they already form part of national, regional and global observation networks.

This is the case with many fishing vessels that have been recruited into fishery and oceanography observing systems around the world (e.g. North Atlantic, Mediterranean Sea, North Pacific) to assist with the collection of physical, biogeochemical and biological ocean data. Many of these collaborations have been successful. But according to Van Vranken et al. (2020^[90]) it is a much underutilised tool and could generate further significant benefits by being extended to the deep ocean and to a wider range of EOVs.

Looking further ahead, recent changes in fishery management approaches are beginning to open the door to much more extensive use of fishing fleets to bolster ocean data collection. In effect, a global effort is underway to shift the fisheries management paradigm away from single species management towards ecosystem-based fisheries management (EBFM). The EBFM concept is to take a holistic approach to management by monitoring and taking into account changes in the physical ocean environment, interactions between ecosystem elements, and impacts from human activity. These physical, biological and socio-economic observations (taken in situ from vessels, coastal observatories, mobile platforms etc. and from satellites) can then be integrated with modelling platforms - for instance, ocean circulation models, ecological models, short-term forecasts - to gain an understanding of the status quo and assess recent and future trends in individual ecosystem elements (Schmidt et al., 2019^[91]). Such integrated ecosystem information offers important guidance for better management strategies, but it also demonstrates the mutual interests and actual and potential benefits to the fishing industry and ocean science alike.

The ecosystem-based fisheries management approach has made huge strides over the last decade in many parts of the world. A recent international OECD survey on fishery policies indicates an increasing focus on resource and ecosystem sustainability. There has been a significant uptake of the ecosystem-based management of fisheries. More than 80% of the countries surveyed considered EBFM an objective in 2016 (compared to about 50% in 2005) and around half of countries reported that they now apply it in practice (compared to only 10% in 2005) (Delpeuch and Hutniczak, 2019^[92]).

Given the rapidly growing momentum behind EBFM and the huge numbers of fishing vessels in operation across the world, there are undeniably tremendous opportunities to make better use of fishing activities in collecting ocean data. This might even apply to improving knowledge of deep-sea habitats, which are increasingly the target of commercial fisheries. As Levin et al. (2019^[14]) point out, fishing vessels could serve as potential research platforms, since crews often possess the requisite skills and experience to deploy and recover various kinds of deep-sea scientific equipment, such as specialized cameras on longlines and sophisticated acoustic systems used in seabed mapping, or attaching equipment to fishing gear which logs environmental information.

It would be important however to ensure that such data gathered from fishing vessels eventually be linked to other ocean observations in a more comprehensive ocean observing setting, within the framework of the Global Ocean Observing System and other regional ocean observing efforts, not least with a view to acquiring an improved global understanding of fish abundance and distribution in the ecosystem context (Schmidt et al., 2019^[91]).

Deep sea mining

As things stand at the time of writing, seabed-mining operations are only under way in countries' exclusive economic zone (EEZ), There are no mining operations in the Area Beyond National Jurisdiction (ABNJ), which falls within the remit of the International Seabed Authority (ISA). However, numerous exploration activities are ongoing (International Seabed Authority, 2019^[93]). At this stage, explorations offer opportunities to raise the frequency and coverage of deep-ocean observations, generating substantial benefits for deep-sea science. New species are discovered almost every day.

Already in the exploration phase, institutional and commercial contractors are obliged to share some of their findings, and provide a range of biological, physical and chemical deep-ocean baseline data, both for ascertaining the environmental and commercial viability of potential mining projects, and as a pre-requisite for securing permits for later exploitation (ISA, 2020^[94]). The ISA is active in harmonising those data, thereby adding considerably to the volume of available regional deep-ocean data provided by its contractors as part of exploration activities. Hence, at the exploration phase, there is already a high level of bilateral collaboration between specific contractors and ocean-science institutions (Levin et al., 2019^[14]).

There is however room for improving science-industry co-operation in the exploration phase. Partnerships might for example be extended to international level by creating multi-stakeholder working groups with a focus on one or more of the potential seabed mining regions such as the Clarion Clipperton Zone or West Pacific seamounts. They could tie into existing relevant networks (e.g. ISA, Deep Ocean Observing Strategy (DOOS) network, etc.) to co-ordinate actions among stakeholders, or work to bring together industrial operators with established global ocean observation networks (e.g. Argo and OceanSites networks) (Aguzzi et al., 2019^[76]).

The objective might be the launch of a joint demonstration project or even the installation of an observatory. Indeed, most of the zones with commercial potential do not yet possess a truly multidisciplinary, deep-water seafloor observatory infrastructure (Levin et al., 2019^[14]). Yet, if mining operations were to begin and monitoring and exploration activities were to multiply, so would the demand for relevant ocean data grow to track any environmental impacts.

Hence a strong case of mutual benefit can be made for establishing as soon as possible long-term seafloor and/or water column observatories in potential mining zones to expand temporal and spatial coverage of ocean observations, and build scientific evidence on the state of deep sea marine ecosystems.

Changing the ocean data paradigm

As ocean data volumes increase in the coming years, more will need to be done to maximise their utility and value to ocean science, economy and society. Although the international Argo array changed the paradigm on global availability and many networks followed suit, numerous factors threaten to impede future efforts to develop ocean data's full potential. Although these factors need to be slightly nuanced by discipline, they include: limited access to and sharing of data particularly for biological data; lack of standardisation and interoperability; risks to data integrity and data security; uneven distribution of knowledge, know-how and technologies.

Limited access to and sharing of ocean data

The basic argument for making ocean observations available to users on a free and unrestricted basis is that open access encourages wide use of data and the development of new data products (deYoung et al., 2019^[86]). There is a widespread expectation that publicly funded data should be freely available and easy

to access (OECD, 2020^[95]), however it is still not the case today for some ocean datasets in different parts of the world.

There are still substantial obstacles to data access and use within the ocean community as well as between the ocean community and other communities of ocean data users, with fragmentation and many different sources. Although the situation may vary depending on the types of observations, overall what is required for ocean data is a shift in the current paradigm for transforming data into information and thence into knowledge, thereby stimulating the creation of new information frameworks and a re-think of how people use and gain value from data. For that to happen, the key question needs to be resolved as to how to make ocean data that are “difficult or complex to find, understand and use, available to anyone in a way that makes sense to them” (Buck et al., 2019^[10]). This in essence is the “data democratisation” challenge, where artificial intelligence and Machine to Machine readable data will play a key part.

Also, lack of publicly available data combined with big differences in approaches to data access, as well as inefficient data sharing practices, conspire to impede some researchers’ ability to detect changes over time and space. It remains difficult to build usable time-series, make the regional comparisons and perform the global assessments on which management and policy decisions depend (Muller-Karger et al., 2018^[8]).

Progress is being made. As Muller-Karger et al (2018^[8]) point out, many countries have agreed to international data open-access agreements, for example the IOC Oceanographic Data Exchange Policy, and the Global Earth Observation System of Systems (GEOSS). Yet large volumes of biological and biodiversity data fail to meet full accessibility standards, such as being available in global databases like the Ocean Biodiversity Information System (OBIS), or in usable, sufficiently disaggregated form in terms of time and space. Specifically on OBIS, which offers the possibility to integrate and make accessible standardised data on marine biodiversity, an upgrade (OBIS 2.0) is under development that offers scientists the capacity to process data and conforms to international standards database conforms to international standards (e.g., OBIS-ENV-DATA format of Darwin Core). The system is being taken up by several interested organisations including the European Marine Observation and Data Network (EMODnet), Fisheries and Oceans Canada (DFO), the US Integrated Ocean Observing System (IOOS), and the Integrated Marine Observing System (IMOS) in Australia (Muller-Karger et al., 2018^[8]).

Moreover, a big advance has been achieved in the establishment of guiding principles for scientific data management and stewardship – the FAIR principles, according to which data should be findable, accessible, interoperable and re-usable. Once implemented, the result should be more rigorous management and stewardship of valuable digital resources, which will be of benefit to the entire academic community by supporting knowledge discovery and innovation (Wilkinson et al., 2016^[96]). The principles are finding their way into the ocean science domain and there is a growing need for harmonization in the many ocean observing data management structures (Tanhua et al., 2019^[97]). For example, the recently established Ocean Best Practices System operates on the basis of the FAIR principles; and the ambitious proposal for an integrated all-Atlantic ocean observing system by 2030 makes the FAIR principles central to its envisaged Atlantic Ocean data management system (deYoung et al., 2019^[86]).

Nonetheless, the scope for improving marine data access and sharing is vast, and efforts need to be stepped up significantly if the anticipated surge in ocean data of many different types is to be harnessed to the full. All stakeholders need to be involved, be they scientific research, industry, international organisations or networks, public authorities, NGOs or foundations. Fundamentally however, to achieve the desired data paradigm shift, a change in culture is also required, a change in mind-set which injects a disruptive approach into data sharing (Pendleton et al., 2019^[98]).

A particularly important role can be played by governments and policy makers in enhancing access to and sharing data. The recently revised OECD’s *Recommendation concerning Access to Research Data from Public Funding* adopted by forty countries in early 2021 aims to establish access and global sharing of

research data as a major policy priority, with the ultimate goal of making the global science system more efficient and effective (OECD, 2021^[99]). The revised Recommendation expands its scope to cover not only research data, but also related metadata (data about data, specifying their sources, methodology and limitations), as well as the bespoke algorithms, workflows, models and software (including code) that are essential for their interpretation. This will contribute to further to enhancing access to and sharing of ocean data.

The OECD also provides an overview of the many policy avenues open to governments to directly effect change in its recent review of government initiatives across some 37 countries relating to data access and sharing, with associated benefits and risks (OECD, 2019^[100]). Many governments have been leading by example in investing in the facilitation of data sharing within their public sectors, but also in facilitating or regulating data access and sharing with the private sector. In some cases, this has been achieved through voluntary and collaborative approaches, in others through data sharing partnerships within the private sector, notably via public-private partnerships. Some governments have focussed on raising analytic capacities right across society, improving skills and infrastructures, establishing and collaborating with data analytic support centres, and supporting innovation and R&D in data analytics. Yet others have brought about greater policy coherence through new national and sectoral data strategies.

The diversity of case studies documented suggests that management of ocean data could benefit substantially from experience and insights gleaned in other sectors where initiatives are already in place. Other promising initiatives include the [C4IR Ocean](#), a network of 13 centres around the world developing innovative projects that leverage cooperation among industry, academia, government and the public aim to harness rapidly emerging digital technologies for improving ocean health, resilience and economic productivity. The C4IR Ocean flagship project is the Ocean Data Platform, which is working with Microsoft to make ocean data more easily accessible for decision-making and provide open source software and tools to explore and analyse ocean data.

Standardisation of data and interoperability

For data systems to interact properly, there have to be standardised rules for complete consistent metadata as well as self-describing data formats, so that different types of data can be synthesised into a single archive (Levin et al., 2019^[14]). However, some present-day data management practices fall short in many respects. Many management systems accepting broad data types may be designed specifically for a narrow specification, with the result that delays can occur in data receipt and some data and metadata can go missing if the specification is not met precisely. (deYoung et al, 2019) In Levin et al's view (2019^[14]) "there is a pressing need for standardized metrics, implementation of common nomenclature within and across fields, improved provenance tracking, and the application of real-time quality control".

Some progress is being made, and J. Buck et al. (2019^[10]) point to numerous examples including:

- the Global Ocean Observing System (GOOS) are advancing with the development of EOVs; SeaDataNet and EMODNet are moving to cloud-based services and user-defined data products (Vance et al., 2019^[101]);
- the International Oceanographic Data and Information Exchange (IODE) programme of IOC UNESCO, working through its distributed network of National Oceanographic Data Centres (NODCs), has established the Ocean Data Portal (ODP) which aims to implement "end to end" data management and a "one-stop shop" system to facilitate seamless access to marine data/services and to promote the exchange and dissemination of marine data and services using agreed-upon formats. This distributed system allows all member systems to harvest from each other data to seamlessly create new datasets ;

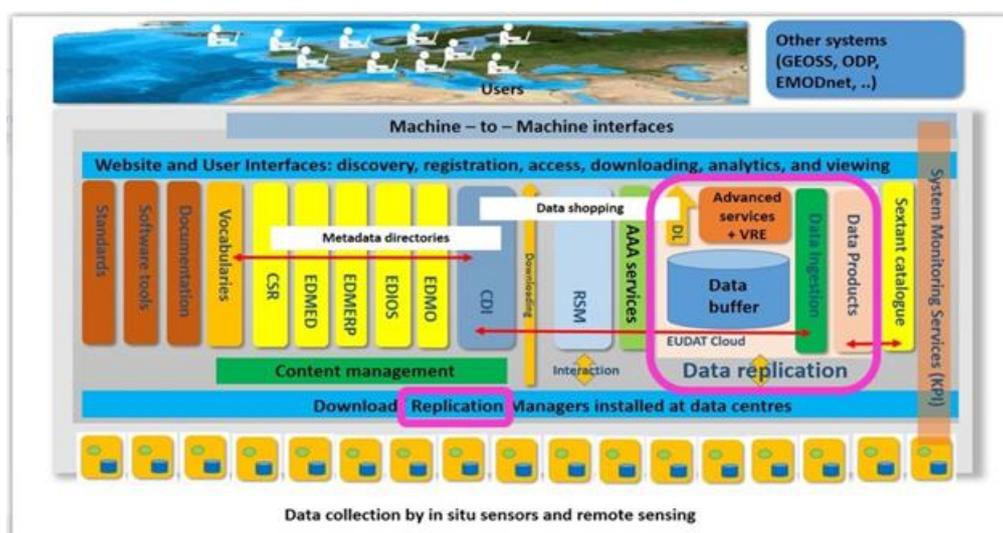
- the FAIR principles (see previous section) whose successful implementation necessitates the use of controlled vocabularies and ontologies, standardized data, and standardized access protocols to support widespread uptake and long-term use;
- the NeXOS project (cited earlier) which inter alia integrated optical and acoustic sensors on ocean gliders and profilers, thereby making it possible to automate the installation, processing and dissemination of data through standard software suites and tools.

However, much more needs to be done in terms of strengthening ocean community standards, as they form the basis for interoperability. Indeed, there are calls for all new data systems to be interoperable (deYoung et al., 2019^[86]) as this would greatly benefit data exchanges within and between observation networks, as well as encouraging the spread of user-friendly data tools.

In terms of regional-scale upgrading of data standardisation and interoperability for the future, the EU's SeaDataNet is a useful illustration of what can be done. SeaDataNet brings together more than 100 ocean observing data centres in 34 countries into a Pan-European infrastructure that offers up-to-date, high-quality access to ocean and marine metadata, data and data products from marine observations ranging from ocean physics to chemistry and biology. It does this through common data management standards, and technical and semantic interoperability with other relevant data management systems. The current phase of the project (2016-2020) envisages, as noted above, the adoption of cloud and High Performance Computing technology (SeaDataNet, 2017^[102]).

Similarly, the United States is developing a coherent strategy to integrate marine data streams across disciplines, institutions, time scales, and geographic regions. Such a strategy is considered vital to the success of IOOS and other regional, national, and international ocean and coastal observing systems. As part of the initiative, and to facilitate public access, a Data Management and Communication system has been set up to help IOOS researchers and partners make their data available online on the basis of common standards, formats, and data services (Interagency Ocean Observation Committee, 2017^[103]).

Figure 2. SeaDataNet planned updated architecture with data replication, advanced services and Virtual Research Environment in the cloud



Source: SeaDataNet (2017^[102]).

Best practices as a foundation for standards

A community best practice is defined as a methodology, usually originating through a bottom-up process in an individual organisation, that has repeatedly produced superior results relative to others with the same objective, and has been adopted and employed by numerous organisations. Best practices can become standards if approved and established by standards organisations or equivalent (Buck et al., 2019_[10]). Hence, best practices complement standards in supporting improved interoperability and data/information exchange (Pearlman et al., 2019_[104]).

Best practices offer a multitude of benefits for ocean data. Those range from greater consistency and interoperability among measurements on all spatial scales – local, regional and global – to efficiency gains in day-to-day operations by reducing duplication of effort and unnecessary repetition of learning processes. And applied across value chains, they support faster, more efficient research and product development. Moreover best practices complement standards in that they have a faster adoption period and can adapt more flexibly to emerging technologies (Pearlman et al., 2019_[104]; Buck et al., 2019_[10]).

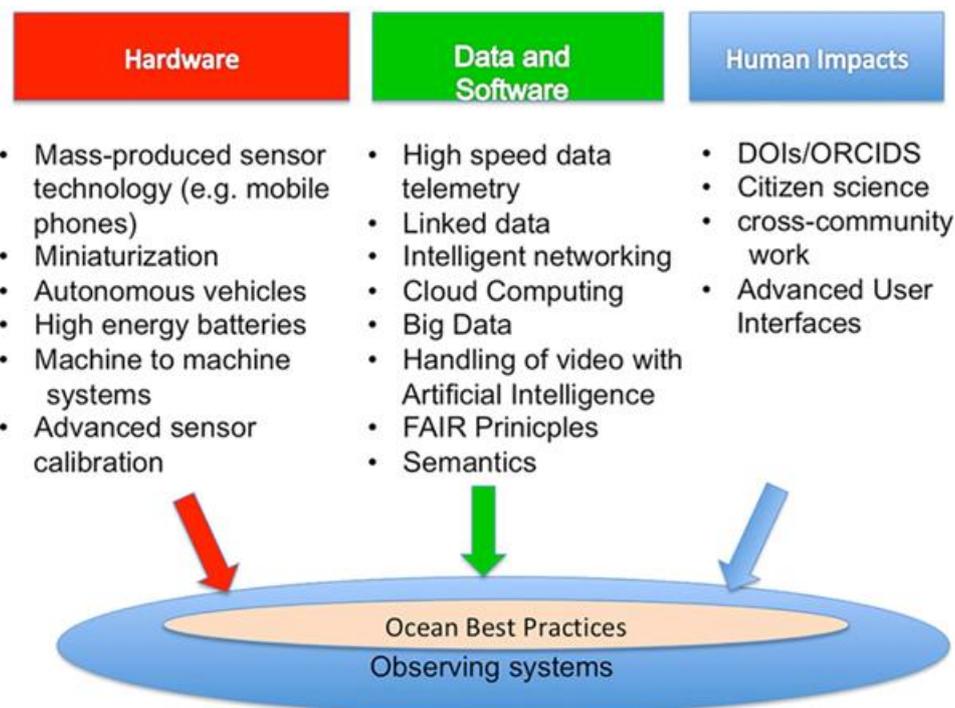
A prime requirement for regional- and global-scale collaborative ocean observing is to have in place well-defined and reproducible methods across activities. However, the ocean best practices landscape is fragmented – many groups have developed best practices, but they are scattered around the Web, often difficult to find in local repositories, and many are unavailable in digitised form. What observing activities require is careful structuring so as to enhance their efficiency, coherence, and coverage (Pearlman et al., 2019_[104]).

A major step forward has been achieved with the creation of a new global system – the Ocean Best Practices System (OBPS), which comprises: repository archive; user-friendly interface; advanced technology including text mining and semantic tagging; peer-reviewed journal linked to the repository; a training component supported by the OceanTeacher Global Academy and a community forum. The OBPS is an open access, permanent, digital repository of community best practices in ocean-related sciences and applications maintained by the International Oceanographic Data and Information Exchange (IODE) of the UNESCO-IOC as an IOC (IODE, GOOS) project. OBPS offers an array of services in discovery, access and training of Best Practices working with the technical communities that originate and use best practices. IODE and GOOS work with many of the prominent institutes, networks and organizations that are the source of ocean data and information. OBPS is a focal point for the ocean data community, harmonising the formats of best practice documents and ensuring their contents are exposed to the Web (OceanBestPractices (OBP), 2020_[105]).

Looking to the future, the role of best practices and the OBPS are expected to play a vital role. As Figure 3 indicates, many new technologies are emerging and becoming more mainstream (e.g. cloud computing, AI, machine autonomy, high-speed data telemetry). They will necessitate a new generation of documented methods and processes, as value-chain components become ever more interlinked, marine-related disciplines and data types become more integrated, and remote and autonomously configurable sensor-to-sensor systems call for more advanced quality control processes (Pearlman et al., 2019_[104]).

Such an expansion of technologies and services will need to go hand in hand with an expanded set of best practices. That in turn, will need to be guided by international consensus, opening up further opportunities for a more active role of the OBPS.

Figure 3. Advances in the next decade will enhance ocean observing and impact best practices evolution



Source: Pearlman et al (2019^[104]),

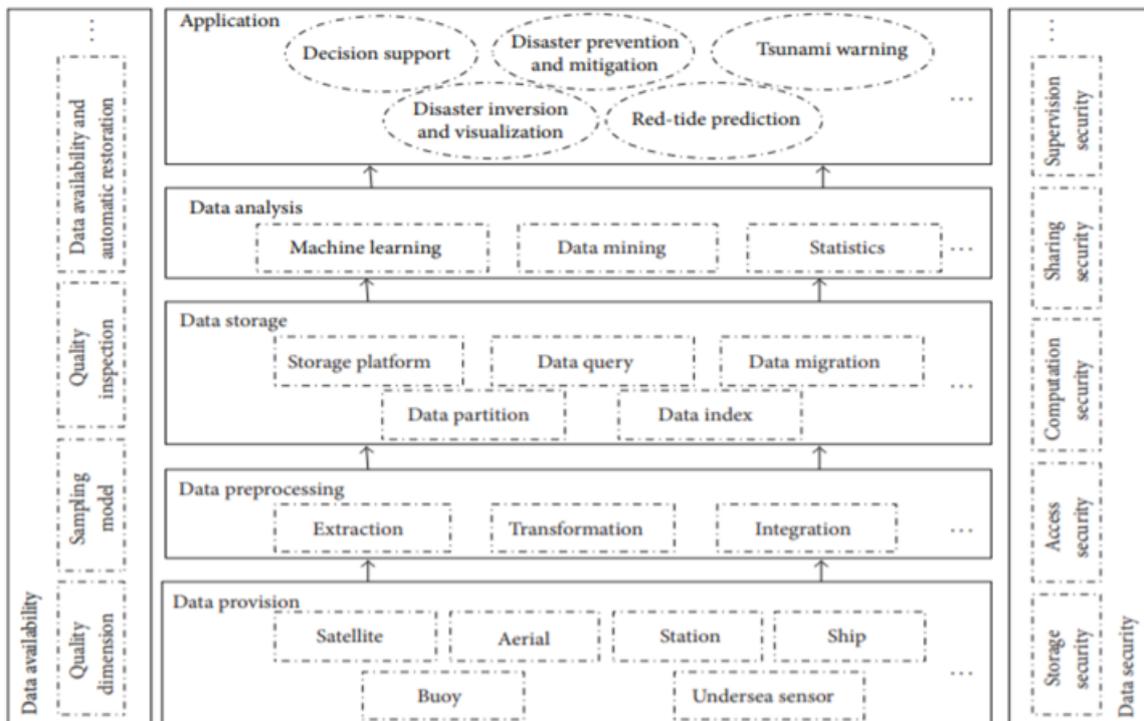
Data integrity and security

The vision of an interconnected ocean populated by a multitude of low-cost, easily configured and deployed sensors and other instruments and platforms is an appealing one, and it provides momentum to the drive towards improved data access, sharing, transmission, processing and storage. Such interconnectedness however goes hand in hand with a greater need for data quality control, integrity and security. Without such safeguards, trust in the data and therefore their role both in monitoring change and supporting decision-making at all levels, from management to policy formulation, will be undermined. User trust is paramount. Yet security of the Internet of things (IoT) in ocean observation is still in its infancy (Buck et al., 2019^[10]).

Ocean observation already produces big data and volumes of data collected will grow even greater as observation capabilities expand around the world. Management of big data, on the other hand, is still at an early stage of development. Consequently, almost all current research into marine big data is focussed on solving general big-data management issues (Huang, 2015^[106]). Research into data security, however, is underdeveloped. Yet data security is fundamental to the entire data management system. As Figure 4 illustrates, it is crucial to all the component processes - data storage, data access, data computation, data sharing, and data supervision.”

Yet research into data security is underdeveloped. As the interconnected ocean moves ever closer to reality, efforts to maintain data quality and integrity and render marine data systems much more secure, will need to be stepped up substantially.

Figure 4. Marine big data architecture



Source: Huang, Song and Zou (2019_[107]); Huang et al, (2015_[106]).

Capacity building

Knowledge and skills in the ocean community will be an essential ingredient in meeting the challenge of significantly upgrading the spatial/ temporal coverage, output quality and user value of ocean observing in the years ahead. For the more advanced economies of the world, this is chiefly a matter of sustaining and continually developing and/or adapting scientific and technological education and training to keep pace with dynamic change in the innovation landscape.

For less advanced economies, the task is much more demanding given the disparate opportunities – financial, economic, political and technical – that persist among countries. As Levin et al. (2019_[14]) point out, international networks and organisations (UNESCO/IOC, IODE, WMO, GOOS, JCOMM, POGO, to name but a few) already offer capacity-building training programmes for ocean observing in developing regions. But the scale of the task is vast. In many parts of the world vital to improving our understanding of ocean processes, variables and habitats, no or very little ocean observing takes place, not least because of the lack of local scientific and technological capabilities across almost all relevant fields – marine biology, chemistry, environmental sciences, data management, and many more. Capacity building will prove an important plank in any strategy for the coming decade.

4 Covid-19 and the outlook for ocean science, research and observation

As of early 2021, Covid-19 has affected billions of people and caused well over a million fatalities worldwide. Many more cases are expected as the second wave of the virus runs its course in those countries already severely affected, and the virus takes further hold in the developing world where health infrastructures and response capacities are far less developed than in most of the advanced economies.

So far governments have mobilised unprecedented levels of funding to tackle the virus and counter its health, social and economic impacts (see the [OECD COVID-19 Hub](#) for data, analysis and recommendations concerning the crisis and ongoing responses). Companies too have taken on much more debt as they struggle with business disruption, revenue losses, and the impact of successive lockdowns. As a result, global debt has surged. Government and companies have taken on borrowing in 2020 likely to total around 20 trillion USD by the end of 2020, raising the global debt-to-GDP ratio from 320% at the start of the year to 365% end of year (Institute of International Finance, 2020_[108]). Nonetheless, annual economic growth rates are expected to plummet to extraordinarily low levels in most countries in 2020, and some years may pass before pre-crisis GDP levels are reached again.

How the overall economic picture unfolds over the coming decade is of vital interest to the ocean economy, to research, innovation and observation, especially as the UN Decade of Ocean Science for Sustainable Development approaches. Given the high degree of uncertainty surrounding the next few years, building a strategy is fraught with difficulties. Nonetheless, based on developments so far in early 2021 and the lessons of previous economic crises, a speculative glance into the future points to the likely emergence of a range of possible issues that may need to be addressed.

By way of illustration, despite the successful trials underway with several vaccines, there is little prospect of the pandemic being brought under control before mid-2021, except in a few countries in Asia, Europe and Oceania. The economic consequences will still be rippling through the global economy just as the UN Decade for Ocean Science gets underway. The main risk for the ocean observing community is probably budgetary, since the lion's share of its funding stems from governments/public agencies. With high levels of debt resulting from Covid-19-related government spending, effects on future government expenditure will be significant even if much of the debt servicing is spread over generations, as seems likely based on current plans.

For quite some time, government spending will be lopsided, bending strongly towards dealing with the consequences – economic and particularly social – of the pandemic, and in particular aiming to strengthen national health systems more durably and cushioning the effects of companies' and workers' lost earnings. In spring 2020, scientific personnel, researchers and resources from various disciplines were being diverted to strengthen the resources being devoted to addressing the search for Covid-19 treatments and vaccines. Moreover, perhaps with the important exception of some medical science and research activities, science and research budgets may see further cuts in government support. As for business R&D, evidence from past deep economic downturns this century suggests that the percentage share of total R&D spending by companies tends to fall more steeply than the decline in GDP (OECD, 2020_[109]).

In such circumstances, the ocean science and observation community will find it hard to make a successful case for an increase in public funds, not least because much of what it does is targeted to the long term. Climate science could be pushed into second place behind medical science and research, at least for a while, although recent Green New Deals are being developed in different countries, and it cannot be excluded that some of the large tech companies that have actually benefited from the pandemic may turn their interest to ocean matters. In succinct terms, ocean observation is likely to live through much of the UN Decade of Ocean Science with limited room for manoeuvre on funding.

Especially in light of the setbacks to business and likely decline in business R&D noted above, the economic challenges facing ocean-based industries constitute a further risk to the funding and operations of ocean science and research. Many of those industries such as offshore oil and gas, offshore wind, fisheries, tourism, shipping, ports and so on are already under strain from an almost perfect storm of circumstances – cutbacks in industrial and commercial activity as a result of social distancing measures and collapsing markets, a remarkable downturn in oil and gas prices triggered by competition among key oil and gas producers, a rapidly spreading global recession, and climate change proving increasingly disruptive.

For some time to come, ongoing and planned industry projects are likely to experience reductions, deferrals or outright cancellations of capital investments. That could shrink the room for manoeuvre in terms of industries' willingness to enter into collaborative arrangements with ocean science, unless the benefits were overwhelmingly positive and the risks, where present, clearly delineated.

This is not to say that there will be no potential opportunities for such collaborative ventures even under such adverse conditions. Industrial and commercial strategies to cut personnel and reduce the involvement of human resources in operations by introducing new automatic and autonomous technologies, could help stimulate technological innovation and research. Equally, postponing big resource exploitation projects in the ocean (e.g. oil and gas, wind power, seabed mining) might widen the time-window of opportunity available to intensify exploration activities and environmental assessment, and improve preparations for investments when the time is ripe.

This paper has set out in some detail many of the steps that will be needed to sustain the current innovation momentum in the digital ocean economy into the future, and to ensure in particular the continuing acquisition of ocean data and knowledge required for a deeper understanding of our ocean and seas and their conservation and restoration. However, it is already apparent at the time of writing that the Covid-19 pandemic has the potential to impinge on and indeed jeopardise many of the efforts and initiatives described in Part 3, notably where substantial ongoing and new funding is needed.

To help mitigate the impacts of such a tightening of budgets and of diminishing opportunities for collaboration with industry, the following actions might be considered: prioritise projects generally considered as critical; focus on low-cost solutions where possible; expand user engagement; leverage existing infrastructures and ocean observation networks; strengthen horizon scanning for innovations and existing technologies that might be adapted to ocean research purposes; target critical science and technologies for extra support (e.g. artificial intelligence); encourage and support efforts to enhance standardisation and best practices, especially where they promise considerable cost-savings and efficiency gains. In more detail:

- Aim for a broad consensus regionally/internationally that allows to identify which projects should get priority in which geographical areas to maximise returns (in terms of data and information): for example, new observation infrastructure in the Arctic because of the ocean basin's rapid pace of change and its critical role in climate change; or strengthening observing infrastructure in the tropics because of the abundance of biodiversity present there; or filling gaps in sensor coverage (e.g. previously neglected geographical locations, or water column, benthic or coastal etc.) considered to become critical in the near future.

- Prioritise research into and diffusion of low-cost sensors and platforms.
- Accelerate low-cost deployment of sensors and platforms e.g. by enhancing multi-functionality of sensor systems, multiple payloads on mobile platforms/infrastructures, etc.
- Expand low-cost user engagement e.g. citizen science, joint projects with industry, use of industry infrastructures for installing sensors, for example by stepping up efforts to systematically identify opportunities for science and industry collaboration.
- Prioritise observing system integration where this leverages existing ocean infrastructure capacity to generate high benefit-to-cost ratios.
- Focus on international collaboration to leverage co-operation for achieving greater efficiency and/or coverage of existing observation infrastructure (e.g. AtlantOS proposal) rather than on the creation new expensive infrastructures (which could be put on hold for a period of time).
- Raise the efficiency of innovation research by targeting capacity in specific research areas, especially but not only AI.
- Further strengthen horizon-scanning for scientific and technological innovations in other sectors of the economy which could be transferred to/re-purposed for use in ocean observation.
- Exploit opportunities presented by speeding up the momentum towards greater standardisation and the development of best practices, thereby improving data acquisition, data analysis and data products, as well as operational efficiencies, at relatively low cost.

5 Concluding remarks

Digital technologies for ocean-related data acquisition, numerical simulation and analysis are progressing rapidly on multiple fronts. For the foreseeable future, it will be possible to capture ever increasing volumes of data from the ocean and, with concomitant progress especially in AI, analysed quickly and effectively. Putting together all these advances in sensors, platforms, autonomy, systems integration and analytical capacity into a functioning and effective digital system of ocean data collection, analysis and action holds great promise for the future of the ocean economy and the planet more generally.

However, that promise is unlikely to be fulfilled unless strong supportive, organisational and collaborative action is taken across a wide range of areas focussing on:

- reducing cost and scaling up production volumes of sensors and other instruments;
- strengthening industry-science collaboration to expand ocean observation coverage;
- improving access to and sharing of data; encouraging data standardisation and interoperability;
- and tackling risks to data integrity and data security; and addressing the current highly uneven geographical distribution of knowledge, know-how and technologies.

Unfortunately, the Coronavirus pandemic, its impacts and counter-measures have the potential to impede if not derail those actions. Among the biggest threats are shifts from long to short term priorities in science and research and cuts in public financial support to ocean science research and innovation. Steps can be taken to mitigate the consequences of such measures, notably by re-thinking priorities among the larger projects, targeting low-cost solutions, strengthening science-industry collaboration and partnerships, expanding user engagement, and so on. But big opportunities could be missed.

Recent months have seen huge economic stimulus packages announced to support, inter alia, ailing businesses, and the coming years should see yet more stimulus packages of this kind. Unsurprisingly, that has been seized upon in many quarters as a massive opportunity to accelerate the climate change effort through more green investments. In allocating stimulus funds, governments can prioritise green projects, for example, and/or impose green “conditionality” by attaching environment-friendly terms to the granting of funds.

To the extent that such a greening of economic stimulus packages is successfully accomplished, there is ample opportunity for ocean science and research to benefit. Government stimulus funding could be steered towards relevant ocean research projects, and where ocean-based industries are the beneficiaries of such spending, opportunities to intensify or re-configure science-industry partnerships could be identified and exploited for ocean research and observation activities. For that to happen, the ocean science and research community itself will need to become highly proactive in its search for such opportunities.

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