State of the Ocean Report 2022

Pilot edition

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Intergovernmental Oceanographic Commission

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

Published in 2022 by the United Nations Educational, Scientific and Cultural Organization 7, place de Fontenoy, 75352 Paris 07 SP, France

The report should be cited as follows: IOC-UNESCO. 2022. *State of the Ocean Report*, *pilot edition*. Paris, IOC-UNESCO. (IOC Technical Series, 173)

Graphic Design: Ana Carrasco
Cover design and typeset: Ana Carrasco
Cover photo: Mountains over the sea © Unsplash/Ian Schneider
Printed in UNESCO printshop, Paris, France

(IOC/2022/TS/173)

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Table of contents

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Foreword

Vladimir Ryabinin
Executive Secretary of the IOC of UNESCO
Assistant Director-General of UNESCO

Scientific knowledge illuminates the way to reversing the decline in ocean health, conserving marine life, addressing ocean aspects of climate change and using the ocean sustainably to improve people's lives. Related international environmental conventions are informed by major multi-year assessments, such as the UN World Ocean Assessment, IPCC and IPBES reports. However, international policies must also to be turned into actions – globally, regionally, nationally and locally. Best practices in ocean management should be increased and shared in a timely manner, and at all scales. In order to build on the momentum of these essential activities, it is crucial to keep the general public, stakeholders and governments fully informed of the quickly evolving situation in the ocean, and what is being done.

The Intergovernmental Oceanographic Commission (IOC) of UNESCO is the 'home' of ocean science within the UN. Its secretariat coordinates and facilitates the development of many systems and programmes for observing, studying and managing the ocean. IOC-affiliated programmes support the generation of ocean data and knowledge, which help to build solutions to known problems and identify emerging issues in ocean science. IOC Member States are continuously expanding their work in managing and protecting the ocean, which means that the IOC is uniquely positioned to initiate and coordinate a much needed periodic publication to inform the world about the current state of the ocean, and to do so in a more dynamic way than was previously possible. This is the main idea behind the *State of the Ocean Report* (StOR).

The StOR proposal was first presented to the 53rd Session of the IOC Executive Council in February 2021. The concept was further elaborated for consideration by the 30th IOC Assembly in June 2021 and received unequivocal support from IOC Member States. This pilot StOR, which will be considered by the 55th Session of the IOC Executive Council in June 2022, is the result of strenuous efforts on the part of the IOC Secretariat and leading experts in the broad family of IOC constituencies. Having seen the Pilot, I believe that the StOR will help to efficiently monitor the progress of the UN Decade of Ocean Science for Sustainable Development, 2021–2030, and, in time, can become a seminal and eagerly anticipated worldwide publication that will contribute significantly to mobilizing global society to act towards 'ocean we need for the future we want'. Correspondingly, the best course of action for subsequent editions would be to invite contributions from a number of UN agencies and professional organizations, turning StOR into a pan-UN publication, and to launch the new annual StOR report on the eve of World Oceans Day (8 June) to achieve the maximum impact.

Let me warmly congratulate the IOC on this new achievement and offer my grateful thanks to all those who contributed their talent, energy and goodwill to this pilot edition of StOR!

Executive summary

Vladimir Ryabinin, Henrik Enevoldsen, Kirsten Isensee, Ikroh Yoon

This pilot edition of the *State of the Ocean Report* (StOR) was proposed and developed to demonstrate the feasibility of keeping the world up to date on the current state of the ocean. Building on examples from IOC-led or joint initiatives, the report is structured around the initial Challenges of the UN Decade of Ocean Science for Sustainable Development, 2021–2030.[1]

The StOR reveals a lack of reliable benchmarks in many aspects of ocean knowledge. Most sections in the report tend to be descriptive and qualitative, consistent with the recent seminal Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Assessment (IPBES, 2019) that stated: 'human actions threaten more species with global extinction now than ever before'. The IPBES further elaborates: 'marine ecosystems, from coastal to deep sea, now show the influence of human actions, with coastal marine ecosystems showing both large historical losses of extent and condition as well as rapid ongoing declines (established but incomplete)'. Indeed, a key conclusion from the pilot StOR is that ocean knowledge is generally able to identify ('establish') issues but falls short of these being comprehensive and, hence, actionable ('incomplete') – 'one cannot manage what one cannot measure'.

There is, therefore, an urgent need for a *quantitative* description of the state of the ocean, with established benchmarks and the capacity to report changes. The overall aim remains – to produce (probably annually) a brief, accessible, one-stop overview of the current state of the ocean, and to mobilize global society to act towards 'the ocean we need for the future we want' as a contribution to sustainable development, and in particular to Sustainable Development Goal (SDG) 14. To achieve this, the StOR must be more encompassing. So, for subsequent editions, the IOC will invite contributions from UN agencies and professional organizations, turning the StOR into a pan-UN publication.

A summary of the key findings of the pilot StOR and recommendations for future actions is outlined below.

Challenge 1
Understand and beat marine pollution

There is indisputable evidence of the continued, widespread and unabated increase of land pollution in the ocean. Nitrogen, phosphorus and plastics pollution are reviewed in the StOR. They have become ubiquitous, and their impact on marine life in all its forms, with consequences for human health, is discernible. Studies of various types of ocean pollution present a complex picture of the interaction between natural and anthropogenic sources. Despite the global significance of ocean pollution, observations remain limited, geographically and thematically, being mainly concentrated at the ocean surface and in coastal areas. While a realistic 2-D representation of pollution is becoming a possibility, a 3-D view is still beyond reach. Very little is known about other types of pollution except those reviewed in StOR, e.g. medicaments.

In order to be able to support actions against ocean pollution and enable the meaningful use of existing and emerging legally binding instruments on ocean conservation, a more resourced and systematic approach to observations and synthesis of ocean pollution is urgently required.

Challenge 2
Protect and restore ecosystems and biodiversity

The analysis of marine ecosystems and biodiversity focused on ocean acidification, deoxygenation, evolution of phytoplankton, and progress in quantitative knowledge of marine life. Like marine pollution, current observation systems and data holdings show a complex pattern of variability and change, which modern science can only present in a limited fashion.

This complexity which derives from various types of stressors – including acidification, deoxygenation, warming, more stable water stratification and circulation changes, fishing, habitat destruction, invasive alien species and underwater noise, – acting both individually and as interacting multiple stressors, is shaping the current evolution of marine biodiversity.

1 This pilot StOR covers nine of the ten Decade Challenges, with the exception of Challenge 3, which examines how the ocean's role can be optimized to sustainably feed the world's population. This aspect is not covered by IOC mandate and therefore not addressed in the pilot edition.

IOC-affiliated networks have successfully increased capacity in monitoring and reporting to the United Nations on the state of ocean ecosystems at indicator level. For ocean acidification, an internationally established methodology and standards for SDG indicator 14.3.1 are available, and 308 stations in 35 countries report the pH of ocean water. However, countries still do not regularly produce the data.

An overall picture of evolving marine life is emerging from observations, especially through the use of new eDNA techniques, modelling and data syntheses. To date, approximately 240,000 marine species have been recognized, with roughly 2,000 new species being described every year in all ocean basins. Trends of oxygen depletion, distinct acidification of the open ocean, complex changes in the food web and migration of species to colder waters are 'established' facts. However, the adjective 'incomplete' (IPBES, 2019) best describes the current state of knowledge of ocean ecosystems. The need for ocean ecosystem conservation and restoration is clearly a very high priority, but to make it effective, systematic observations and research need to be strengthened and resourced. In that sense, the UN Decade of Ocean Science is a prerequisite for achieving the marine goals of the UN Decade on Ecosystem Restoration.[2]

Challenge 4
Develop a sustainable and equitable ocean economy

Systematic research in support of a sustainable ocean economy is in its early stages. Not much is known in terms of channels for return on investment, main beneficiaries, related legislation, and market interests and mechanisms. The StOR reviewed two representative issues for ocean economy: the current development of marine (maritime) spatial planning (MSP) and current understanding of the economic value of ocean observations.

Key IOC-led meetings on MSP were held in 2006 and 2017. The earlier event launched the global process of MSP design, creating elements and guides for implementation, while the 2017 conference capitalized on the knowledge and experience acquired and began to develop MSP on a previously unseen scale, primarily through the MSPGlobal Project and the related Joint (IOC-European Commission) Roadmap to Accelerate MSP Processes. To date, approximately 300 initiatives in 102 countries/territories, including government-led processes and pilot exercises, have started and are in different stages of development. The time has now come to look again at the experience gained and lessons learned. One of these lessons is simple: 'one size does not fit all'. Despite the success of MSP, a need has emerged to adapt approaches to MSP globally. The new typology of MSP, based on ten criteria, was tested in association with StOR through a review of eight MSP processes in seven countries. MSP will be a key accelerator of the sustainable ocean economy.

Identifying the symbiosis between the ocean economy and science requires a better understanding of scale, and areas of return on investment in marine science and its practical applications. The pilot StOR includes a brief review of current levels of understanding in the economics of ocean observation. In the same way as ocean ecosystems, the fact that a better observed, understood and managed ocean provides longer-term and financial benefits can be considered 'established', but knowledge in this area is incomplete and fragmented – even the methodological approach is not yet in place. In the short term, progress can be made in this area through i) insights into ocean economy accounting; and ii) designing new approaches and capacity development for sustainable ocean planning and management, both at the national level and for the high seas.

Challenge 5
Unlock ocean-based solutions to climate change

The pilot StOR considers one significant area of climate change solutions – the coastal blue carbon ecosystems. Forty million hectares of these ecosystems are found along the coastline of continents, housing mangroves, salt marshes and seagrasses. These hotspots for carbon storage have sequestration rates per hectare that are up to ten times larger than those of terrestrial ecosystems.

It is clear that internationally coordinated research has been able to achieve a more precise quantification of location, area, state and potential of carbon sequestration, segregated for these three types of ecosystems. Improved protection and management of coastal blue carbon ecosystems can reduce current total carbon emissions by

2 UN Decade on Ecosystem Restoration https://www.decadeonrestoration.org/

up to 2%. However, due to urban and industrial coastal development, pollution and pressures from agriculture and aquaculture, 20–50% of global blue carbon ecosystems have already been lost or degraded. While it is possible to note a reduction in the loss of mangroves, currently at 0.11–0.13% annually, new findings have identified unacceptably high rates of loss of salt marshes, at 1–2% annually, and an even more dramatic loss of seagrasses, at 2–7 % annually, due to pollution of coastal waters and destructive fishing practices.

Challenge 6
Increase community resilience to ocean hazards

Concise analyses of sea level rise, warning systems for storm surges and tsunamis, and harmful algal blooms (HABs) corroborate conclusions from the previous StOR sections related to pollution, ecosystem health and climate change. They clearly show that coastal resilience is under threat, and coastal populations are becoming increasingly vulnerable due to a combination of environmental factors and patterns of development, including migration to the coastal zone, growth of cities and aggressive human interaction with the ocean.

It is possible to report evidence of a recent acceleration in sea-level rise, both by *in situ* networks (IOC GLOSS) and satellite altimetry. The 1901–1990 pace of global mean sea level rise was of the order of 1.3 mm/year, with subsequent acceleration to 3.3 mm/year from 1993–2002 and 4.7 mm/year from 2013–2021. The superposition of various 'fingerprints' from larger and smaller scale processes, along with the additional impact of local natural and anthropogenic changes, creates a highly complex pattern of regional and local sea-level rise.

The IOC tsunami warning and mitigation system is growing and now comprises 12 tsunami service providers in 4 regional tsunami warning systems. Such a system will only work if coastal communities react efficiently to warnings. This requires public awareness and preparedness – four tsunami information centres, one in each tsunami region, contribute to this. The ambitious objective of the IOC TsunamiReady Programme – 100% of coastal communities at risk of tsunamis to be recognized as 'tsunami ready' by 2030 – is a critical contribution to the resilience of coastal communities globally. Currently, 30 communities have been recognized as tsunami-ready.

Significant advances have been made in understanding and quantifying the variability and predictive capacities of HABs. Statistical analyses of 9,503 HAB events in the period 1985–2018 and 5 million microalgal records (as a proxy for observational efforts) reveal a lack of any uniform *global* trend in the number of HABs. The focus should therefore be on the regional scale, where a statistical relationship was found between the trends of harmful algal events and aquaculture production.

The above conclusions are of direct relevance to coastal ocean (zone) management. A central feature of these management systems should be a coastal observing and prediction system, addressing a broad range of hazards related to storms, tsunamis, and pollution accidents such as oil spills, harmful algal blooms, etc. Elements of such systems exist locally and regionally but these need to be replicated for other coasts that are currently not covered. Given that even a small longer-term background sea-level rise significantly increases the risk of extreme shorter-term events, such as storm surges and tsunamis, upgrading coastal defence infrastructures must be seen as a priority. With time, the combined risks of coastal hazards will only increase, and a comprehensive risk assessment and management system that can also address real-time events will become a key factor in the sustainability – and even the survival – of coastal communities.

Challenge 7 and 8
Expand the Global Ocean Observing System and create a digital representation of the ocean

The pilot StOR reviewed the state of *in situ* ocean observations under the Global Ocean Observing System (GOOS), progress in using the FAIR principles (Findability, Accessibility, Interoperability and Reusability) of observing data management, status of ocean data sharing under the International Ocean Data and Information Exchange Programme (IODE), and progress in seabed mapping.

The current ocean observing system embraces around 10,000 ocean observing platforms, with some 84 countries contributing to the system. The Physical Essential Ocean Variables are the most developed. Biogeochemical observations are expanding, and we have recently seen the arrival of 12 Biological-Ecological ocean observing networks. The observing system provides essential data and products to weather, climate and ocean forecasters, maritime commerce, fisheries and coastal communities. However, there are major gaps in coverage and the system is not currently able to provide data where it is most needed, namely in areas with high biodiversity and intense human pressures. Data, particularly on ocean biology, remain precious and in very limited supply. This correlates well with the conclusions on progress towards Challenges 1 and 2: we can *establish* certain facts based on the current observing system but quantitative knowledge is *incomplete*. The system is very much based on research (i.e. unsustainable) funding, on top of which the Covid-19 pandemic will leave an irreparable scar in ocean climatic data records. Therefore the use of FAIR principles needs to be promoted and publication of data in the Ocean Biodiversity Information System (OBIS) must be facilitated at all levels.

The world of ocean science is at the beginning of an ocean data revolution. The IODE network is the foundation of the current ocean data holding system, comprising 93 data centres (60 National Oceanographic Data Centres and 33 Associated Data Units, of which 18 are in Africa, 10 in Latin America, and 9 in the WESTPAC region) in 68 countries. Most of these data centres provide data services online and also contribute data to the World Ocean Database and OBIS. The next step will be to turn this system into an intensive data processing enterprise, generating a much needed 'digital twin' of the ocean, creating opportunities for ocean forecasting, and enabling responsible and verifiable ocean management decisions and actions. The Ocean Data and Information System will be the backbone of this development and the IOC Ocean InfoHub Project will spearhead its first phase.

Applying data, models and knowledge requires us to understand the geometry of the planet on which we live. Under the joint IHO-IOC GEBCO, and with the unprecedented momentum in collecting ocean topography data created by the Nippon Foundation – the GEBCO Seabed 2030 project – a major milestone has been recently reached. In the space of six years, from 2015 to 2021, the percentage of total area of the ocean represented by GEBCO gridded data sets has increased from 6.7% to 20.6%. The ultimate aim is to have 100% of the ocean bottom mapped and converted into GEBCO products.

Challenge 9
Skills, knowledge and technology for all

All of the above conclusions and statements on various Decade Challenges indicate an urgent need to increase the capacity of ocean science to successfully contribute to sustainable development. For this to happen, it is absolutely crucial to be able to measure such capacity – a functionality initiated by the *Global Ocean Science Report* and its associated portal. For example, we know that the number of ocean science researchers varies across countries, from less than 1 to more than 300 employees per million inhabitants; and that women account for some 7% to 72% of all ocean science personnel with a global average of 37%, exceeding the overall percentage of female researchers and technical support staff for all sciences, which stands at 33%. The SDG 14.a.1 indicator – the percentage of globally averaged national research budget allocated for ocean science – currently stands at 1.7%. This low value lies behind the difficulties in ascertaining the state of the ocean, as noted in numerous sections of the pilot StOR.

A major step forward for capacity development is the second generation of the OceanTeacher Global Academy (OTGA). This online and blended learning platform organized over 40 online training courses in 2020–21, with more than 1,000 participants from all continents. In 2022, a network of 17 OTGA Regional and Specialized Training Centres has established courses tailored to specific regional needs and is providing training in the languages that are regionally relevant. This system is complemented by five Regional Training and Research Centres in the IOC WESTPAC region, with one more centre under development. Three UNESCO Category 2 Centres in ocean sciences operate in the Islamic Republic of Iran, India and Iceland.

One important way of replicating success in ocean sciences is to use the Ocean Best Practices, a library of methods and a training resource. The corresponding repository, covering physical, chemical and biological oceanography, with a focus on observation as well as many other related applications, is increasingly accessed by various users.

Challenge 10
Change humanity's relationship with the ocean

All the issues noted above are the direct consequence of too little 'understanding of our influence on the ocean and its influence on us', which is one of the Ocean Literacy definitions. Major qualitative advances have recently been made in this area, with the increased availability of toolkits, a readiness to embrace ocean teaching as part of sustainable development in schools, trainings, surveys, strategies, networks, etc.

UN Decade of Ocean Science for Sustainable Development, 2021–2030

At the time of completing the pilot StOR, the Ocean Decade can be described in numbers as a global movement comprising 43 global programmes, nearly 157 projects, 15 UN-led actions, dozens of unique contributions, nearly 300 workshops, training courses, publications and other events, 7 regional taskforces and 28 National Decade Committees.

Key conclusions from the pilot StOR

This pilot StOR is the result of strenuous efforts by the small IOC Secretariat team, supported by contributions from leading experts. It is imperfect, but since its conclusions are important, there is a need to continue this work. Future editions of the StOR will report on progress (or lack of) wherever possible, and will continue to establish benchmarks on the state of the ocean across the globe.

The attempt to create a StOR led to a 'moment of truth'. This pilot edition reveals all too clearly that although society is aware in principle of what is happening in the ocean, and what should be done about it ('established' facts), the quantitative description of the ocean is drastically incomplete and, as a result, current knowledge is insufficient to effectively inform solutions to the ocean issues that humanity is now facing.

Therefore, the way forward is to:

- broadly communicate the findings on the continued lack of quantitative knowledge about the ocean;
- continue to promote and develop the UN Ocean Decade as the prime platform to transform ocean science, so that it can effectively contribute to sustainable development;
- act to create a theoretical basis for sustainable ocean planning and management, within and beyond areas of national jurisdiction, focusing on ocean economy, climate and biodiversity, and develop corresponding implementation plans in consultation with key stakeholders; and
- strengthen the ocean science-policy interface.

Reference

IPBES. 2019. *Global Assessment Report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. E. S. Brondízio, J. Settele, S. Díaz and H. T. Ngo (eds). Bonn (Germany), IPBES Secretariat.

Challenge 1. Understand and beat marine pollution

Understand and map land- and sea-based sources of pollutants and contaminants and their potential impacts on human health and ocean ecosystems, and develop solutions to remove or mitigate them.

Trends of nutrients and eutrophication

Alexander F. Bouwman and John A. Harrison

Nitrogen (N) and phosphorus (P) mobilization due to agriculture, aquaculture and household and industrial wastewater have both increased rapidly in recent decades (Seitzinger et al., 2010; Beusen et al., 2016). The N and P that have played a major role in boosting food production have found their way into nearly every water body across the globe, where they stimulate growth of aquatic plants. This excess plant growth often leads to anaerobic conditions (hypoxia, dead zones), where organic matter decay consumes oxygen faster than its diffusion from the oxygen-rich surface.

There has been a striking increase in occurrences and cumulative surface area of hypoxic events over the past several decades, with improvement in conditions only occurring in a small fraction of coastal systems (Breitburg et al., 2018). Spatially, the highest concentrations of hypoxic events are reported to occur along the east and gulf coasts of the USA, in the Baltic region, and off the coast of Japan (Figure 1.1). There are also regions of hypoxia in the north-west USA, along the coasts of Argentina, and on the south-west and south-east coasts of Australia. There is a surprising absence of reported hypoxia in much of the tropics. This may be due to underreporting resulting from a lack of consistent monitoring efforts in these regions, highlighting a need for both more measurements and models capable of predicting hypoxia in regions with little data.

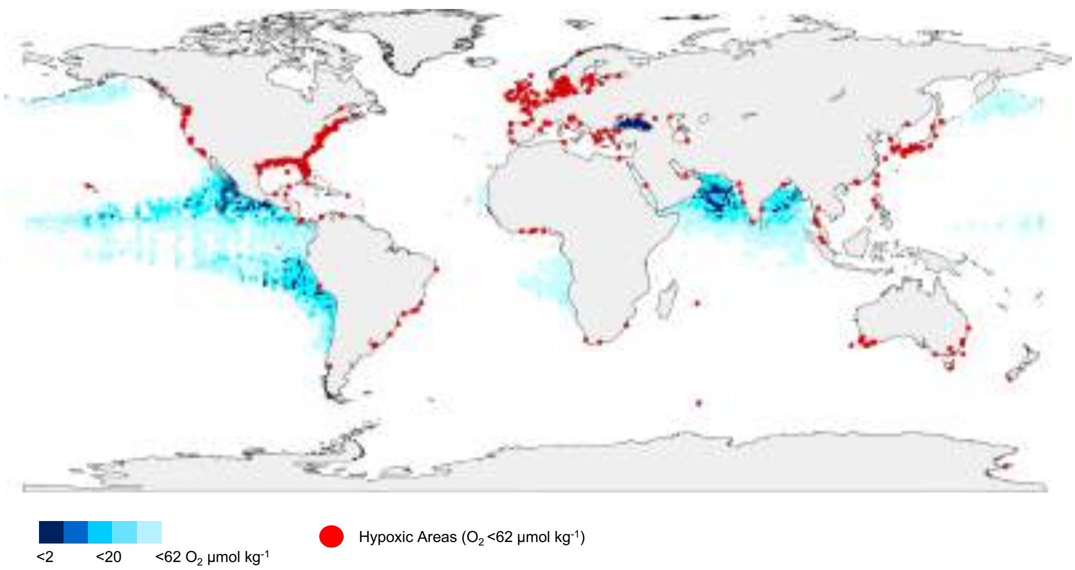

Figure 1.1. Locations of low O_2 areas (i.e. O_2 <62 μmol kg^{-1}) in the coastal and global ocean. In the coastal zone, more than 500 sites have been inventoried with low O_2 conditions in the past half century (red dots); in the open ocean O_2 waters encompass several million km^3 (blue dots refer to conditions at 300 m depth). *Source*: Adapted from Breitburg et al., 2018.

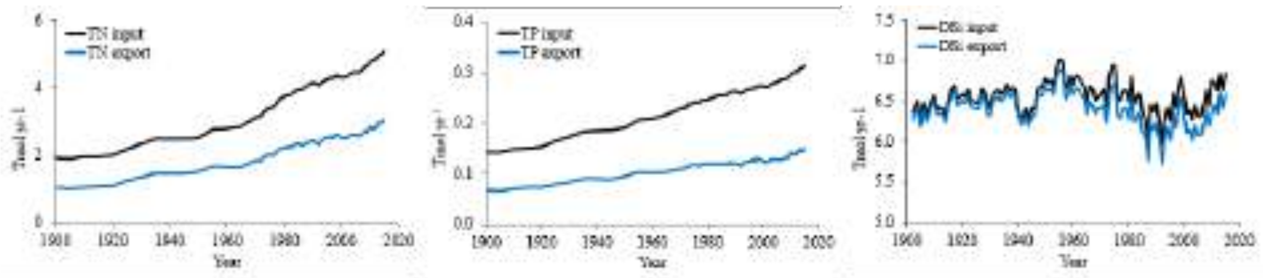

Figure 1.2. Global total N and total P and DSi input into rivers and export to coastal waters. *Source*: N and P data are from Beusen et al., 2022 and DSi data are based on Liu et al., 2020, using a modified model version.

Global N and P delivery to inland waters and river export to the global coastal ocean have increased markedly over the past century, with an accelerated rate since the 1950s (Figure 1.2). In contrast to riverine N and P, which are largely anthropogenic in origin, river loads of dissolved silicate (DSi) come mainly from rock weathering, and hence DSi inputs to rivers have not increased substantially due to human activities. Rather, the construction of dams and the development of reservoirs has decreased large-scale river Si transport, particularly after the 1950s (Conley, 2002). Together, the mobilization of N and P and the increased retention of Si behind dams has caused Si:N and Si:P ratios to decline during the last century (Billen et al., 1991; Garnier et al., 2010).

In addition to oxygen depletion, alterations in the structure of food webs are often observed due to eutrophication in coastal marine ecosystems, with changes in the structure of benthic communities (Lim et al., 2006) and a decline in zooplankton affecting commercial fish production (Rousseau et al., 2000). Habitat loss is a global problem, as there has been a rapid decline of warm-water coral reefs, seagrass meadows and coastal wetlands (mangrove forests and salt marshes) (see Breitburg et al., 2018 and references therein). It is now recognized that these phenomena are not only caused by nutrient enrichment of the marine system per se, but rather by the changes in the proportions in which nutrients are delivered to coastal waters, i.e. nutrient stoichiometry. The Redfield carbon:nitrogen:phosphorus:silicon ratio (molar ratio of C:N:P:Si = 106:16:1:20) is a generalized representation of the approximate nutrient requirement of marine diatoms (Redfield et al., 1963; Brzezinski, 1985). In systems with an adequate supply of Si relative to N and P, diatoms grow quickly. Nutrient loading of coastal waters in proportion to the demand of diatoms (Redfield et al., 1963) can stimulate diatom (and other plant and phytoplankton) production. Under high-production conditions, eutrophication-related problems such as hypoxia and loss of biodiversity can result. In addition, blooms of non-diatom phytoplankton species may develop in waters where N and P are available in excess relative to diatom Si demand. These non-diatoms are generally of lower food quality, less grazed upon, and consequently a larger fraction becomes detritus (e.g. after viral lysis); as a result, there is substantial oxygen demand upon settling and degradation (Officer and Ryther, 1980; Cloern, 2001).

Some of these non-diatom phytoplankton species may be harmful or even toxic (harmful algal blooms, HAB). Harmful algal blooms appear to be increasing in frequency and there is a growing consensus that human-induced eutrophication is at least partially responsible (Anderson et al., 2002; Glibert et al., 2005; Heisler et al., 2008; Glibert, 2017; Glibert, 2020). Due to their harmful or toxic effects, even a modest increase in the abundance of HAB species can promote noticeable differences in ecosystems.

There is mounting evidence that climate change will exacerbate eutrophication and its associated negative impacts (Baron et al., 2013; Michalak et al., 2013). This underscores the need to develop approaches to examine interactions among disturbances and to incorporate ecological principles into management and restoration activities (Stanley et al., 2010). Disturbance of biogeochemical cycles by human activities calls for an integrative consideration of biogeochemical fluxes between the atmosphere, terrestrial and aquatic ecosystems and their impacts.

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Plastic pollution is a threat to marine ecosystems, affecting both environmental and human health

Peter Kershaw and Bethanie Carney

While polymers have been used to manufacture different products for human use since the late 1800s, large-scale industrial production and use of plastics began in the 1950s; the first reports of plastics in the ocean appeared in the early 1970s. Extensive research has shown that plastics are now ubiquitous in marine ecosystems, from surface waters in coastal regions to deep ocean trenches, from the tropics to polar regions (Figure 1.3).

Marine plastics are now considered a key aspect of achieving the Clean Ocean Challenge within the United Nations Decade of Ocean Science. A plethora of publications has provided 'snapshots' of marine litter and microplastic abundance through a wide variety of media in a range of environmental settings. However, attempts to provide a representative overview of the 'current state of the ocean' until recently have been limited to simulations of surface distribution, based on estimated leakage rates into the ocean combined with ocean circulation models (Chassignet et al., 2021). This was the sole basis for informing the single level-1 (global) SDG indicator on floating marine plastics debris (UNEP, 2021).

Most observational data are from shoreline surveys and this represents the category of litter most suitable for widespread harmonization monitoring. Surveys of floating microplastics are the next most common data sets, but the distribution of sample collection points has been limited to certain regions or transects and is not representative of the overall ocean surface. In addition, there is a high degree of spatial heterogeneity reflecting oceanic features such as meso-scale, eddies, wind-induced surface mixing and the formation of windrows. In response, there have been concerted efforts to improve harmonization of data collection methods and to increase data availability at a regional and global scale (e.g. US-NOAA, G20-Japan, EU-EMODnet, GESAMP and UNEP-GPML)[3] and consider marine plastic litter as an essential ocean variable (EOV). This has enabled Isobe et al. (2021) to publish an analysis of over 8,000 observations of microplastic abundance to produce the most comprehensive description of the distribution of microplastics in surface waters (an estimated 24.4 trillion pieces or $8.2 \times 10^4 - 57.8 \times 10^4$ tonnes) (Figure 1.4). This illustrated known areas of accumulation, such as subtropical gyres, but also highlighted many data-poor regions.

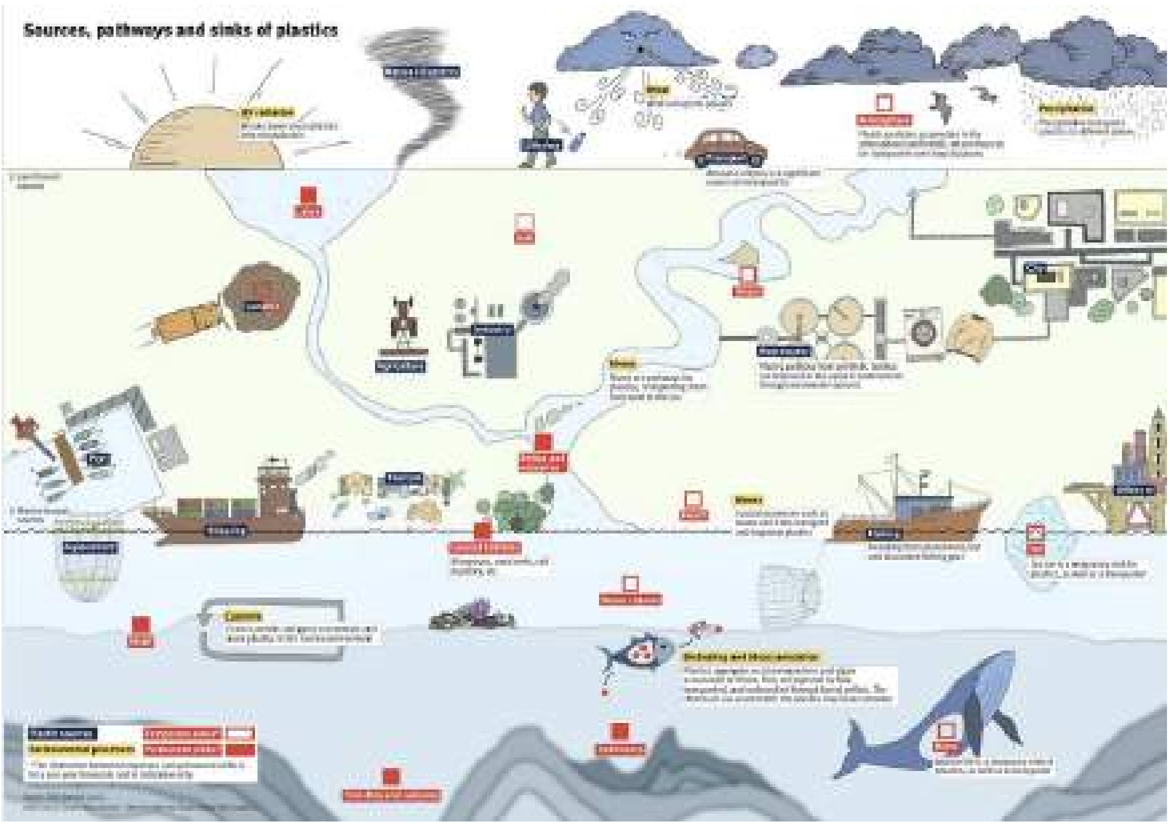

Figure 1.3. Schematic showing the multiple sources and fate of plastic litter and microplastics in the ocean. *Source:* UNEP and GRID-Arendal 2021.

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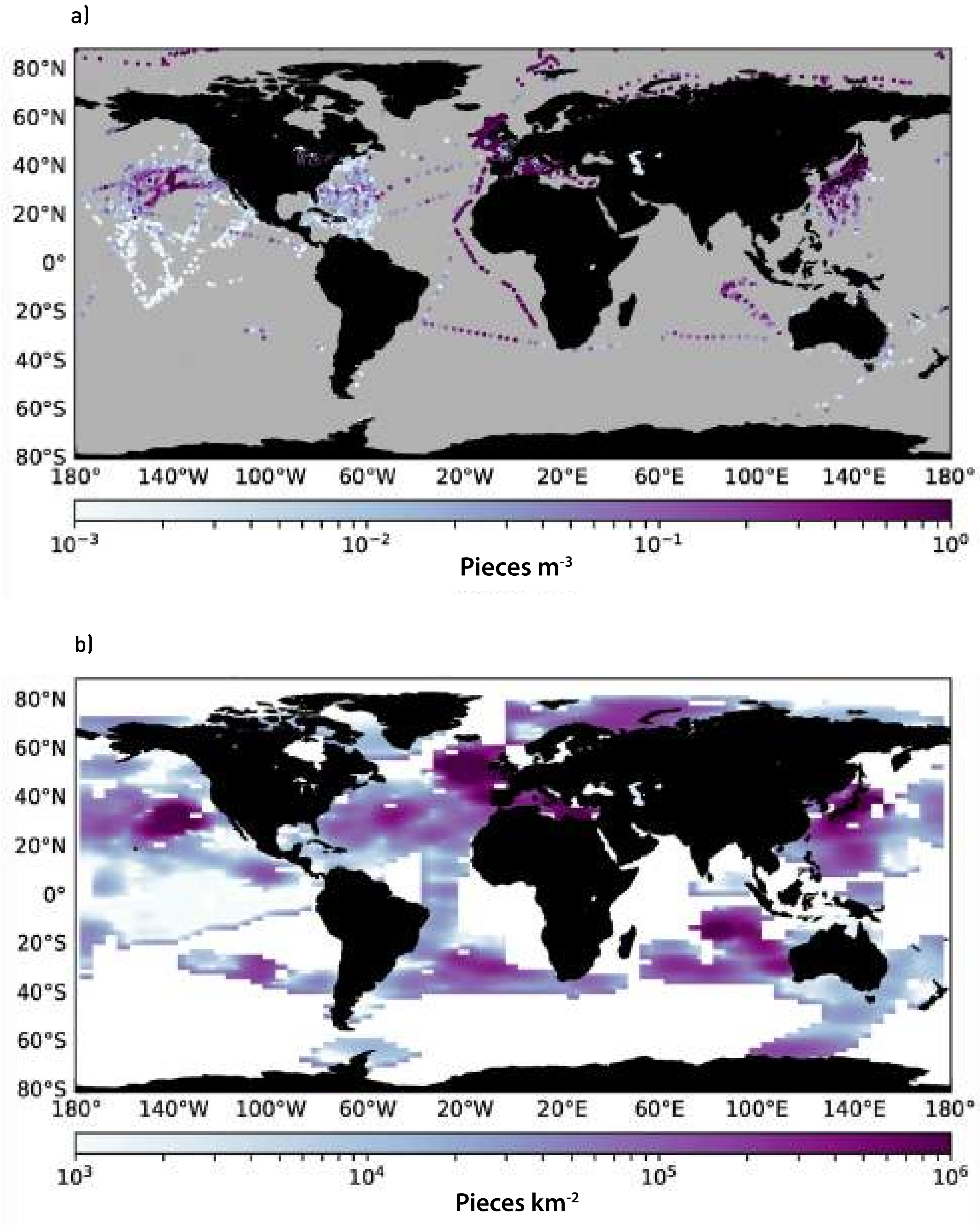

Figure 1.4. Abundance of microplastics in the world's upper ocean and the Laurentian Great Lakes, based on 8,218 microplastic samples. **a)** abundance showing sampling locations; **b)** gridded data based on an optimum interpolation method which yields an estimated 24.4 trillion pieces (8.2 x 10^4 – 57.8 x 10^4 tonnes). *Source*: Isobe et al., 2021.

In addition, very few observations have been made of floating macro-scale litter. The most poorly described region is the ocean floor, with relatively few observations of either micro- or macroplastic litter, due to the practical difficulties and costs involved. However, it is considered to be the destination for much of the plastic entering the ocean. An analysis of 30-year records of deep sea images revealed that about 30–40% of objects were macroplastic, and up to 90% of these, in waters deeper than 6,000 m, were single-use items (Chiba et al., 2018).

Research into the sources, fate and effects of marine plastic litter and microplastics has expanded beyond the natural sciences to include engineering, behavioural and economic sciences, anthropology, governance and policy development.

The presence and impacts of plastic pollution have been highlighted by additional actors, such as non-governmental organizations and civil society groups that can both raise awareness and generate monitoring data (e.g. surfing and ocean sailing communities (Tanhua et al., 2020)). Given the complexity and transboundary natures of the pathways and impacts of marine plastic pollutions, international governance is critical, and several UN entities play key roles, including: UN-DOALOS, UNEP, IMO, UNESCO-IOC, FAO, UNDP, Basel Convention and GESAMP. An important milestone was achieved at the 5th UN Environment Assembly in March 2022, when a resolution to pursue a legally binding global agreement to eliminate plastic waste was agreed overwhelmingly. To achieve this aim, there will be a need to identify realistic and effective solutions that in many cases will need to be tailored to local needs. Given the complexity of plastics production and use in society, the negative impacts on marine ecosystems and human health and well-being, many different actors will be needed (Pewtrust, 2020). Bespoke tools to establish risks and incorporate multiple sources of knowledge will be required, supported by open data resources and interdisciplinary research collaborations.

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Additional resources

- EU-EMODnet **https://emodnet.ec.europa.eu/en**
- G20-Japan **https://www.env.go.jp/en/water/marine_litter/method.html**
- GESAMP **http://www.gesamp.org/publications/guidelines-for-the-monitoring-and-assessment-of-plastic-litter-in-the-ocean**
- UNEP-GPML **https://datahub.gpmarinelitter.org/**
- US-NOAA **https://www.ncei.noaa.gov/products/microplastics**

Challenge 2. Protect and restore ecosystems and biodiversity

Understand the effects of multiple stressors on ocean ecosystems and develop solutions to monitor, protect, manage and restore ecosystems and their biodiversity under changing environmental, social and climate conditions.

Ocean acidification – a global issue with local effects and impacts

Katherina L. Schoo, Jan Newton, Steve Widdicombe and Kirsten Isensee

The ocean absorbs around one quarter of the annual emissions of anthropogenic CO_2 to the atmosphere (WMO, 2021), thereby helping to alleviate the impacts of climate change on the planet (Friedlingstein et al., 2020). The cost of this process to the ocean is high, as the CO_2 reacts with seawater to change the carbonate chemistry of the ocean; this process is referred to as 'ocean acidification' due to the observed decrease in pH. Ocean acidification threatens organisms and ecosystem services, including food security, by reducing biodiversity, degrading habitats and endangering fisheries and aquaculture. Ocean acidification will continue to increase – open-ocean surface pH is projected to decrease by around 0.3 pH units by 2081–2100, relative to 2006–2015, under RCP8.5 (virtually certain), with consequences for the global climate (IPCC, 2019). As the acidity and temperature of the ocean increases, its capacity to absorb CO_2 from the atmosphere decreases, impeding the ocean's role in moderating climate change.

Global efforts are underway to provide society with the evidence needed to sustainably identify, monitor, mitigate and adapt to ocean acidification, led by the Global Ocean Acidification-Observing Network (GOA-ON) and the UN Ocean Decade programme Ocean Acidification Research for Sustainability (OARS). As part of the 2030 Agenda and Sustainable Development Goal (SDG) 14, dedicated to the ocean, the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO) has been identified as the custodian agency for SDG indicator 14.3.1: *Average marine acidity (pH) measured at agreed suite of representative sampling stations.*

The data collected annually by IOC-UNESCO shows a mean global increase in ocean acidification in all ocean basins and seas. While there is an increasing number of ocean acidification observations (308 stations in 35 countries reported in 2022: Data collected by IOC-UNESCO, Figure 2.1), the current coverage is inadequate, with time series not long enough to determine trends and gaps in observations and data found in all areas. The rate of change in ocean acidification, its pattern and scale, shows great regional variability.

A limited set of long-term observations in the open ocean have shown a continuous decline in pH (Open-ocean data: Figure 2.2 a), with an average global surface ocean pH of 0.017–0.027 pH units per decade since the late 1980s. Observations of ocean acidification from coastal areas present a more varied picture (Coastal data: Figure 2.2 b). In addition to absorbing atmospheric CO_2, these coastal areas are subject to a wide range of stressors affecting the carbonate chemistry of the water, such as freshwater influx, nutrient input from agricultural and industrial activities, temperature change, biological activity and large ocean oscillations. More and better distributed long-term coupled observations of chemical and biological parameters are required to discern and map ocean acidification and its impacts, and to develop strategies for mitigation and adaptation at relevant scales .

Regional case study – OSPAR region

The latest Ocean Acidification Quality Status Report (OA-QSR) published by the OSPAR Commission confirms that ocean acidification is observed in the entire North-East Atlantic region (Figure 2.3).

Figure 2.1. Map illustrating surface ocean carbonate chemistry measurement locations received for 14.3.1 ocean acidification reporting: countries which submitted data are colored in blue and dots indicate the location of measurements.

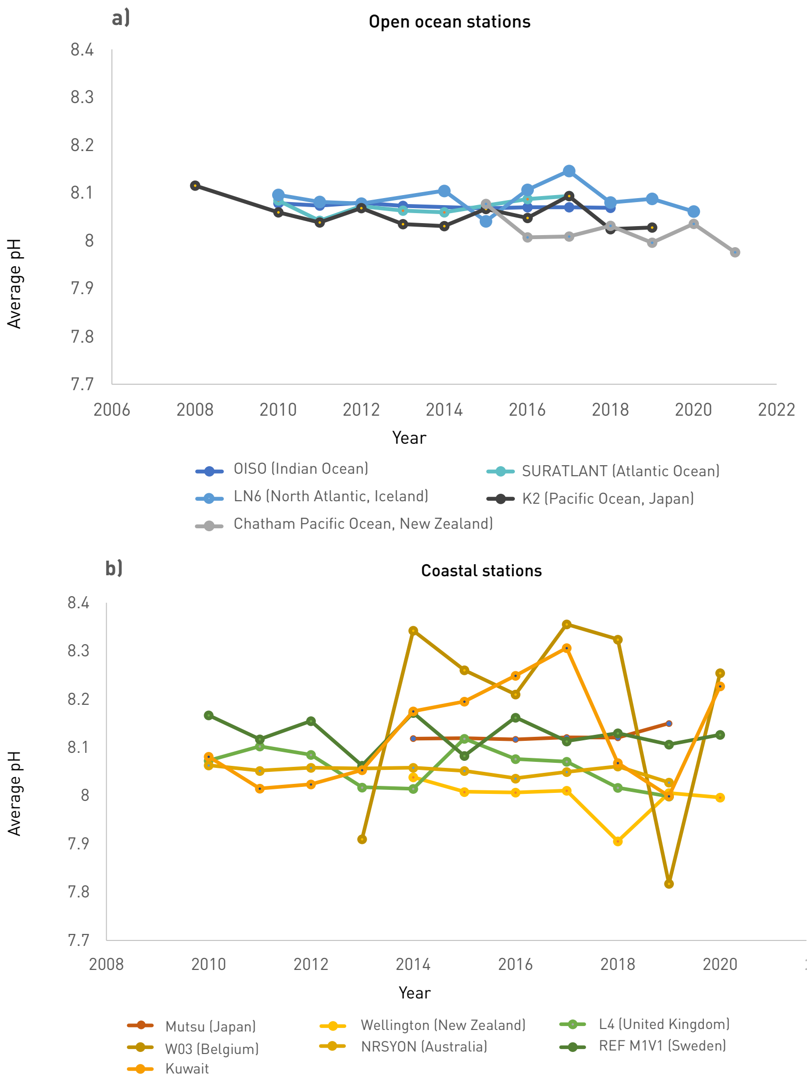

Figure 2.2. Variations in the annual average pH values from a suite of representative sampling stations in open and coastal waters. **a)** Open water Stations: OISO – France, Indian Ocean (data from 2010-2018); SURLATLANT –France, Atlantic Ocean (data from 2010–2018); LN6 – Iceland, Iceland Sea, North Atlantic Ocean (data from 2010–2020); K2 – Japan, North Pacific Ocean (data from 2010–2018); Chatham Island – New Zealand, South Pacific Ocean (data from 2015–2021). **b)** Coastal water Stations: Mutsu – Japan, Sekinehama Port (data from 2014–2019); Wellington – New Zealand (data from 2015–2021); L4 – United Kingdom, Western Channel Observatory (data from 2010–2019); W03 – Belgium, Scheldt Estuary (data from 2013–2020); NRSYON Australia, Yongala National Reference Station (data from 2010–2020); REF M1V1 – Sweden, Reference Station (data from 2010–2020); Kuwait – Kuwait Bay (data from 2010–2020).

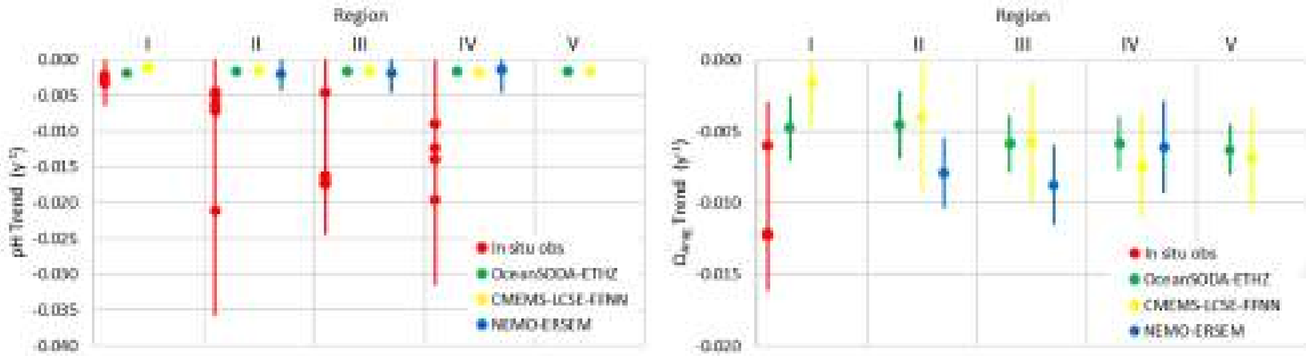

Figure 2.3. Overview on trends in pH (left panel) and aragonite saturation state (ΩArag; right panel) for each of the OSPAR regions (I = Arctic Waters; II = The Greater North Sea; III = The Celtic Seas; IV = Bay of Biscay and Iberian Coast; V = Wider Atlantic) using different data types (in situ observation time-series stations [red], reconstruction synthesis products: OceanSODA-ETHZ (green) and CMEMS-LCSE-FFNN (yellow), and modelling: NEMO-ERSEM (blue)). Trends are only included if they are statistically significant, and for time-series stations only if the station has data for more than 10 years. Note the reconstruction and modelling products are regionally weighted average (mean) trends. Error bars represent standard deviation around the trend). *Source*: OSPAR QSR2023 OA Assessment, in press.

Model projections predict accelerated ocean acidification in the OSPAR region under the higher CO_2 emission scenarios (Figure 2.4).

Studies have shown negative biological impacts on many marine organisms, with clear changes in organisms' structure, distribution and ability to function under ocean acidification conditions. Threatened species and habitats, such as *Lophelia pertusa* cold water coral reefs, are particularly vulnerable to changing environmental conditions, including ocean acidification, and some commercially important species may also be negatively impacted. The OSPAR Commission calls for better harmonized and tailored monitoring and data integration, further integration of observations and model products, and an ongoing multi-strand research effort to better predict impacts to improve understanding of trends, variability, drivers and ecological impacts of ocean acidification.

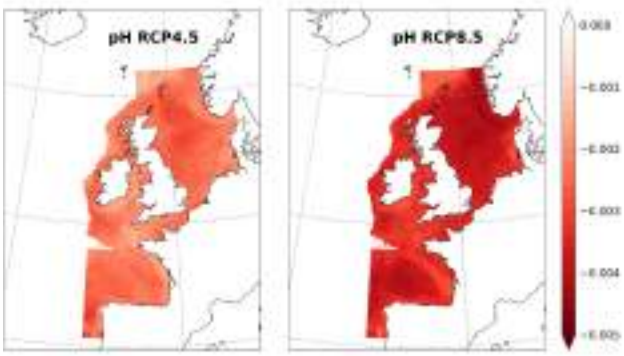

Figure 2.4. Trend of surface pH (yr-1) between 2000 and 2050 as projected by the AMM7-NEMO-ERSEM model under the RCP 4.5 scenario (left) and RCP8.5 scenario (right). Only data within the OSPAR regions has been shown. *Source:* OSPAR QSR2023 OA Assessment, in press.

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Additional resources

- IOC SDG 14.3.1 protal **http://oa.iode.org**
- Global Ocean Acidification Observing Network **http://goa-on.org**
- Ocean Acidification Research for Sustainability Ocean Decade Programme **http://goa-on.org/oars/overview.php**

Deoxygenation in the open and coastal global ocean

Andreas Oschlies and Hernan Garcia

Oxygen dissolved in seawater supports all higher life forms in the ocean, the largest ecosystems on the planet. Dissolved oxygen in surface waters is close to saturation in equilibrium with the atmosphere, which contains more than 99% of the molecular oxygen available on Earth. In the euphotic zone, i.e. the light-lit upper ocean that is in close contact with the atmosphere, photosynthesis can lead to a net production of oxygen. There are no significant biotically-mediated oxygen sources further below in the dark ocean interior. Oxygen concentrations in the ocean interior are generally affected by microbial or higher-trophic level respiration of organic matter, redox chemistry, water advection and mixing. In order to provide sufficient oxygen for all aerobic organisms in the ocean, oxygen has to be physically resupplied from the surface layer via often complex three-dimensional transport pathways. Thus, the spatial and temporal variability of ocean-dissolved oxygen content reflects a complex interplay between physical and biogeochemical sources and sinks.

It is alarming that the ocean is losing oxygen – termed 'ocean deoxygenation' – at a rapid rate estimated at 2% since 1960 (Schmidtko et al., 2017), which is likely unprecedented in Earth's recent history. Decreases in surface oxygen solubility due to human-induced global warming accounts for only about 15% of the observed decline in the ocean's oxygen inventory. Ocean warming also affects stratification and therefore downward fluxes of oxygen and upward fluxes of nutrients needed for biological net primary oxygen production.

The majority of the open ocean oxygen loss seems to be largely caused by physical forcing, such as changes in circulation, mixing and stratification. In coastal systems, biogeochemical processes may also play a significant role (e.g. enhanced supply of nutrients and organic matter from land, biological primary production, respiration and oxidation of labile organic matter). Due to the heterogeneity of coastal systems, quantifying the magnitude and attribution of regional and global deoxygenation variability and trends therein is more difficult.

Deoxygenation may also be affecting the extent of ocean Oxygen Minimum Zones (OMZs) (Figure 2.5) by changing the net balance between oxygen sources and sinks. OMZs are large regions of low oxygen content with oxygen levels often below hypoxic thresholds critical for the oxygen demand of pelagic and benthic communities.

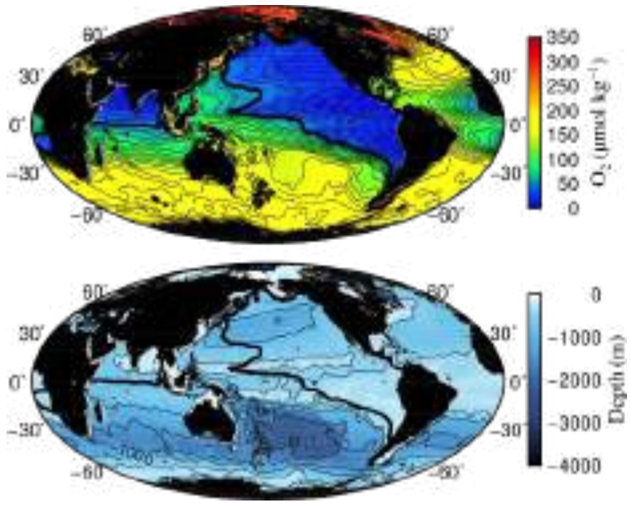

Figure 2.5. Top: Minimum mean O_2 content (µmol kg^{-1}) found in the ocean irrespective of depth. Contour interval is 10 µmol kg^{-1}. Bottom: Depth (m) of minimum O_2 content. Contour interval is 500 m. Heavy contour lines represent boundaries of ocean areas with O_2 content less than or equal to 50 µmol kg^{-1}. *Source*: Garcia et al., 2018.

Quantifying deoxygenation uncertainties, variability and trends would benefit from a sustained international coordinated effort towards building a comprehensive and quality-controlled open-access Global Ocean Oxygen Dataset and Atlas (GO2DAT) complying with the FAIR principles (Grégoire et al., 2021). GO2DAT will aggregate historical and modern global oxygen data of known quality measured by chemical and sensor-based instruments (Figure 2.6). This effort, initiated by GO_2NE,[4] IOCCP,[5] NOAA[6] and the German SFB 754[7] project, is part of the Global Ocean Oxygen Decade (GOOD) programme of the UN Decade of Ocean Sciences for Sustainable Development (2021–2030). GO_2DAT will support the development of advanced data analysis and biogeochemical models for improving our ability to map, monitor and forecast oxygen changes and trends.

4 GO_2NE: Global Ocean Oxygen Network from IOC UNESCO

5 IOCCP: International Ocean Carbon Coordination Project

6 NOAA: National Oceanic and Atmospheric Administration

7 SFB 754: Collaborative Research Centre 754

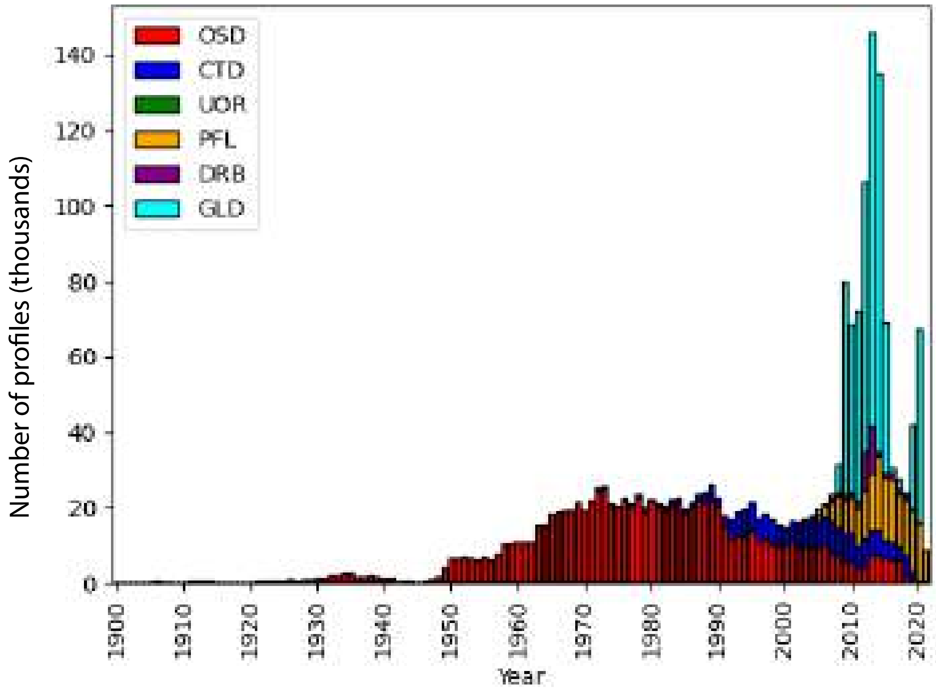

Figure 2.6. Number of O_2 profiles per instrument/platform available in the World Ocean Database (Boyer et al., 2018), as of December 2021. *Source*: All data available at https://www.ncei.noaa.gov/access/world-ocean-database-select/dbsearch.html. OSD = Ocean Station Data (Winkler): 965,078; CTD = Conductivity Temperature Depth: 207,457; UOR = Undulating Oceanographic Recorder: 361; PFL = Profiling Float such as Argo: 194,108; DRB = Drifting Buoy: 38,613; GLD = Glider: 555,597.

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Additional resources

- FAIR principles **https://www.go-fair.org/fair-principles/**
- GO_2NE: Global Ocean Oxygen Network of IOC UNESCO **https://en.unesco.org/go2ne**
- Ocean Oxygen News **https://www.ocean-oxygen.org/**
- World Ocean Database **https://www.ncei.noaa.gov/products/world-ocean-database**

Life in our oceans: Phytoplankton and climate

Peter Thompson, Jacob Carstensen and Hans Paerl

Phytoplankton are the base of the ocean's food chain that provides >90 million metric tonnes of seafood to billions of people, produces ~50% of global oxygen and the sinking of phytoplankton is a major carbon flux. Satellite remote sensing provides global coverage of phytoplankton biomass as chlorophyll a (chl-*a*). From 2002 to 2022, global oceanic chl-*a* showed a low in 2012 and a rise over the last decade (Figure 2.7). Declines in chl-*a* have been reported primarily within the large, low biomass, subtropical gyres (Signorini et al., 2015; O'Brien et al., 2017) potentially due to an increase in stratification (Doney, 2006).

Regionally, the long-term trends in chl-*a* can be strongly positive or negative. For example, chl-*a* has declined in the Northern Indian Ocean, between the UK and Iceland and in parts of the Arabian Sea. In contrast, chl-*a* has increased in many coastal areas, parts of the Southern Ocean and circumglobally along the southern Subtropical Front (Gregg et al., 2017; Dunstan et al., 2018; Hammond et al., 2020). These regional increases in phytoplankton may have many causes, such as changes in runoff, ice cover, wind speed, mixed layer depth and currents (see, for example, Bakun, 1990).

The majority of *in situ* monitoring sites showed 20-year trends of increasing chl-*a* (at 60% of sites), increasing diatoms (67%) and decreasing dinoflagellates (69%), indicating significant changes in community structure (O'Brien et al., 2017). These sites were predominately temperate and coastal, although open ocean coverage is increasing (https://www.cprsurvey.org/about-us/global-alliance-of-cpr-surveys/) and similar results have been reported for the North Atlantic (Barton et al., 2016). A more thorough assessment of global phytoplankton requires more global sampling and improved access to existing *in situ* data (Thompson and Carstensen, 2022).

In the future we anticipate providing spatially resolved trends for phytoplankton biomass (4 km^2 resolution) with basin or regional summaries. Ideally, this would be supported by the analysis of trends in carbon biomass, taxa and biodiversity from the *in situ* sites.

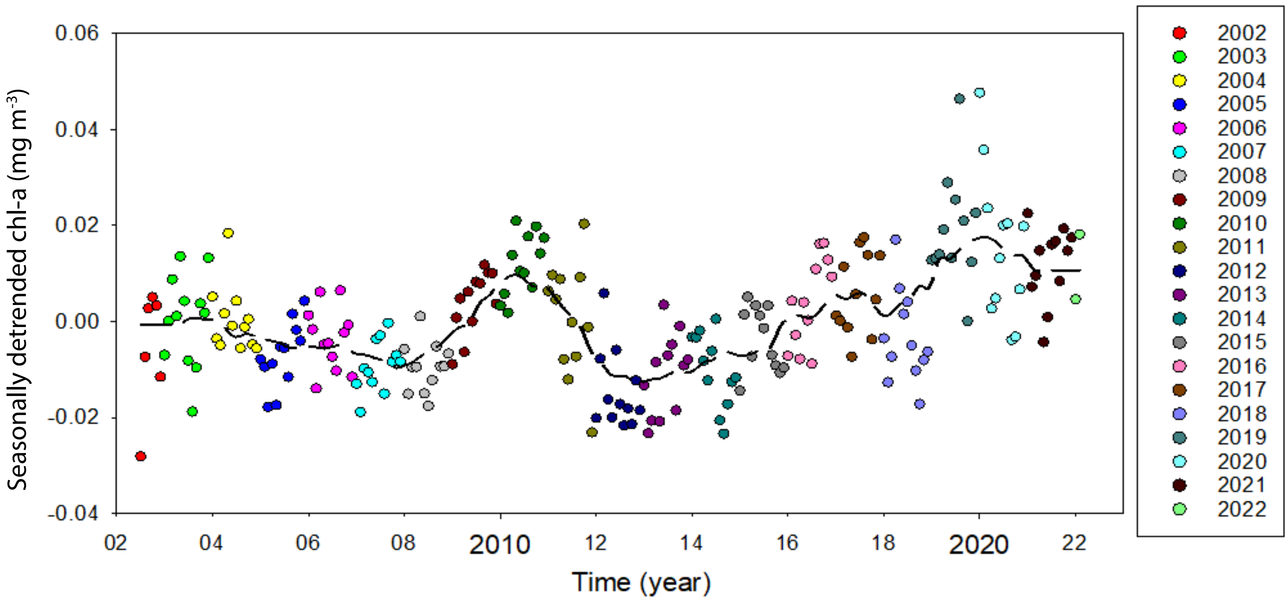

Figure 2.7. Seasonally detrended, global monthly mean values of oceanic chl-*a* from July 2002 to February 2022 (colour coded by year) with a running average (dashed line). *Source*: Analysis based on data obtained via the Giovanni online data system, developed and maintained by the NASA GES DISC.

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New knowledge on and threats to marine biodiversity

Mark J. Costello, J. Tom Webb, Pieter Provoost and Ward Appeltans

Increasing knowledge on marine biodiversity

New field observations and models are improving our understanding of life in the oceans, associated resources, and where, how and why these aspects of biodiversity are changing. Indicators of progress in discovering biodiversity can be obtained from two major databases: the World Register of Marine Species (WoRMS) and Ocean Biodiversity Information System (OBIS), both maintained by a global collaboration among the scientific community.

Over 240,000 accepted species names are recognized in WoRMS, and 160,000 of these species have distribution data available in OBIS. Taxonomic research both synonymizes names and describes new species, thereby reducing and increasing the number of accepted species names respectively. Assessments suggest about one third of marine species remain to be discovered (Appeltans et al., 2012; Costello and Chaudhary, 2017).

Examples of newly described species include mammals, fish, microbes, algae, parasites and a diversity of invertebrates living from the surface to deep-sea[8]. Most species have been described since the 1950s and new species continue to be discovered at a rate of ~2,000 per year in all the ocean basins, both in deep-sea and coastal zones and in previously well-studied areas (Figure 2.8).

The publication of marine biodiversity data continues to increase the number of data records and species (Figure 2.9a–b). New technologies, including satellites, drones, underwater cameras, bio-loggers tracking animal movements, artificial intelligence, and molecular methods such as eDNA, will continue to expand the range of data available (Dornelas et al., 2019). However, there is a time lag before data are published which could be shortened through increased adoption of online data publication, as well as better incentives to publish primary data. Shortening this gap would enable more timely data analyses to better understand trends in marine biodiversity, which is crucial as climate change is now driving rapid changes in species distributions. Furthermore, there is a decline in the number of newly reported species in all ocean regions (Figure 2.9c) that may reflect continued geographic and taxonomic sampling bias. Thus, while there is unprecedented and increasing availability of standardized marine biodiversity data online, many new species are still being discovered, and geographic and temporal data gaps still constrain our ability to fully detect changes in marine biodiversity on a global scale.

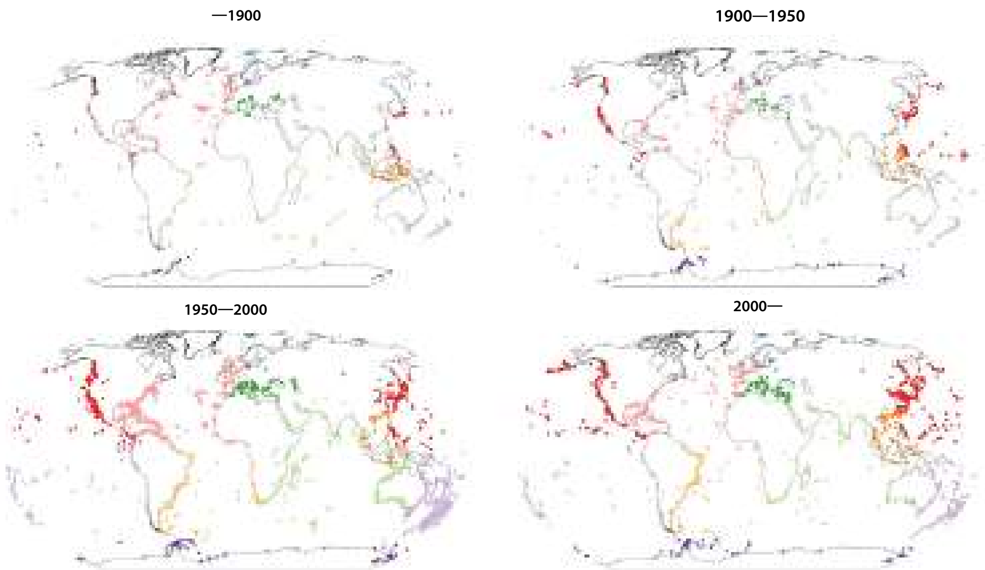

Figure 2.8. World map of type localities of 23,745 marine species over four time periods (prior to 1900, 1900–1950, 1950–2000 and since 2000) based on data from the World Register of Marine Species published in the Ocean Biodiversity Information System. Type localities are where the 'type specimens' from which a species was first named were collected. This shows how marine species new to science continue to be discovered throughout the world's oceans.*Source:* WoRMS Editorial Board, 2021. Type locality distributions from the World Register of Marine Species. Available from: http://www.marinespecies.org at VLIZ, accessed at https://obis.org/dataset/b74b429a-4052-4f5b-bff3-fe0b5a2e8669.

8 https://lifewatch.be/en/worms-top10-2021

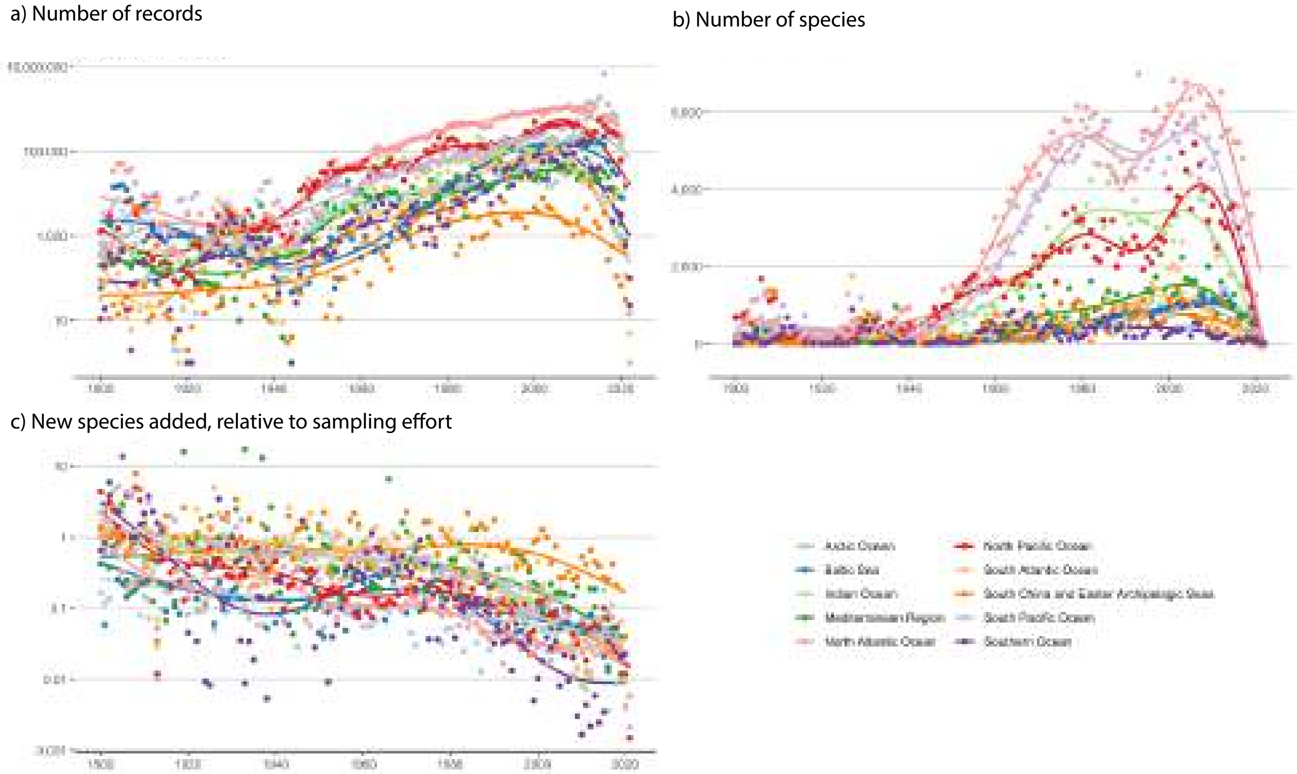

Figure 2.9. The number of records, total species and newly added species relative to sampling effort (equal area grid cells x months), per year by ocean region, based on the Ocean Biodiversity Information System. *Source:* OBIS, 2022. Ocean Biodiversity Information System. Intergovernmental Oceanographic Commission of UNESCO. www.obis.org

Threats and risks to species and habitats

Climate change will continue to drive shifts in the distribution of thousands of marine species, with local extirpation of species and changes to local ecosystems, including regional declines of coral reef and kelp forest ecosystems. Anthropogenic climate warming has been correlated with observed (as predicted) shifts of thousands of marine species from low to mid latitudes, resulting in decreasing numbers of species in low latitudes and an increasing number in high latitudes, especially in the northern hemisphere (Chaudhary et al., 2021). However, the major extinction risk to marine biodiversity remains fishing, both directly and through bycatch and trawling impacts on seabed habitats (Maxwell et al., 2016; O'Hara et al., 2021).

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Challenge 4.
Develop a sustainable and equitable ocean economy

Generate knowledge, support innovation and develop solutions for equitable and sustainable development of the ocean economy under changing environmental, social and climate conditions.

Marine Spatial Planning – A global update and proposed typology criteria

Michele Quesada da Silva, Joanna Smith and Ingela Isaksson

Marine spatial planning (MSP)[9] has progressed significantly since 2006 when it was launched onto the world stage by IOC-UNESCO at the first international workshop on MSP. The first MSP step-by-step guide was then published in 2009 and later, the organization adopted with the European Commission a Joint Roadmap to Accelerate MSP Processes Worldwide[10] (MSProadmap), in line with the UN 2030 Agenda.

For the last decade, IOC-UNESCO has worked with Member States, partners and practitioners to assess the status of MSP around the world. In 2020, for example, the organization sent a survey[11] to its Member States to obtain information about the status of ongoing and new MSP processes. After reviewing these assessments and consulting complementary information (such as Ehler, 2021; European MSP Platform, 2022; Frazão Santos et al., 2019, 2020; The Nature Conservancy, 2022), more than 300 MSP initiatives were identified from 102 countries/territories, including both government-led processes and pilot exercises (Figure 4.1). Most completed plans are in Europe. It was very encouraging to see the number of MSP in early development in Africa, Americas and the Caribbean, Asia and Oceania regions.

An analysis by country revealed that about half are in the early stage of MSP, a quarter are in plan development, and 38 have approved plans (national, sub-national and/or local scale) (Figure 4.2; additional resources: Supplementary material). The number of marine spatial plans reviewed is low – only 14 plans from 10 countries. The MSP initiatives compiled ranged from integrated coastal zone and marine plans, strategic or comprehensive plans, and across multiple geographic scope, political scales and planning objectives.

One of the lessons learned from more than a decade of MSP is that the process and outcomes are not 'one-size-fits-all' around the world. With the aim of improving understanding about the evolution and adaptation of MSP globally and looking towards some consistency for regular reporting, ten criteria were drafted for a typology of MSP (see Additional resources, Supplementary material for detailed description). The objective of developing such criteria is to assess whether there are commonalities, differences and/or trends, not to evaluate each initiative in-depth – a task that needs to be done by the competent authorities as part of the MSP process. Criteria for an in-depth assessment are suggested in the *MSPglobal International Guide on MSP* (UNESCO-IOC/European Commission, 2021).

9 Marine (or maritime) spatial planning is a public process of analysing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives that have been specified through a political process.

10 MSProadmap https://www.mspglobal2030.org/wp-content/uploads/2019/03/Joint_Roadmap_MSP_v5.pdf

11 MSP survey https://oceanexpert.org/document/26529

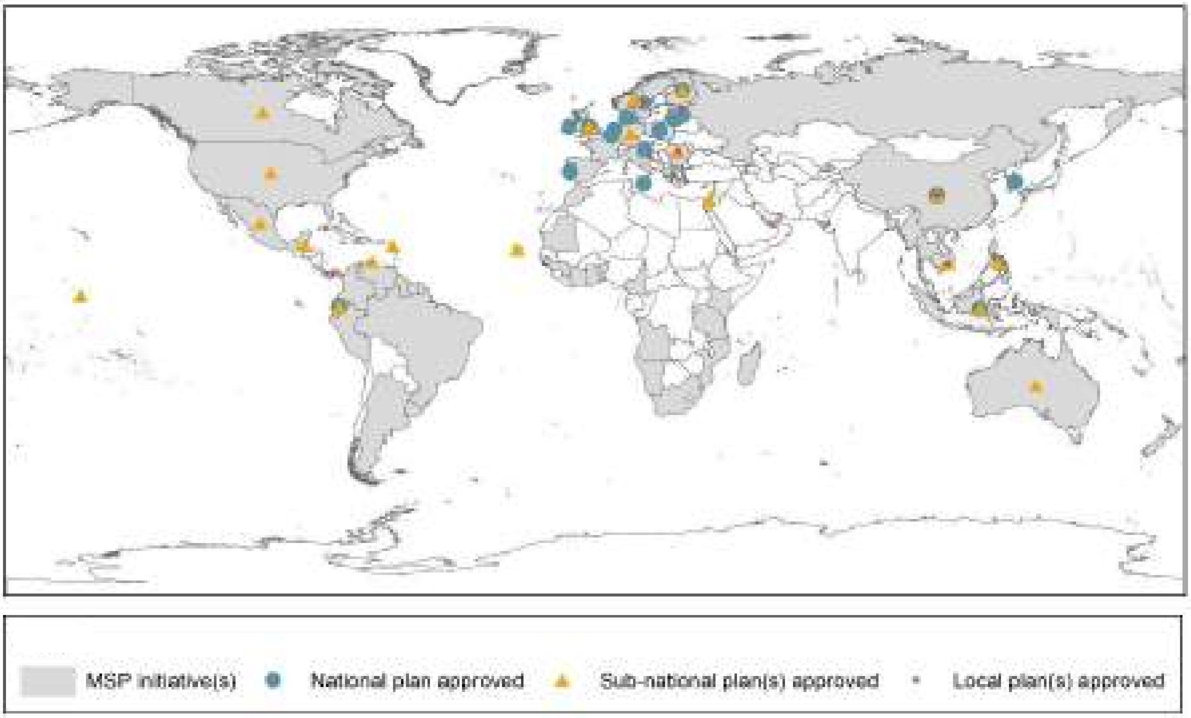

Figure 4.1. MSP status around the world by April 2022. *Source:* IOC-UNESCO and MSP survey, 2022 .

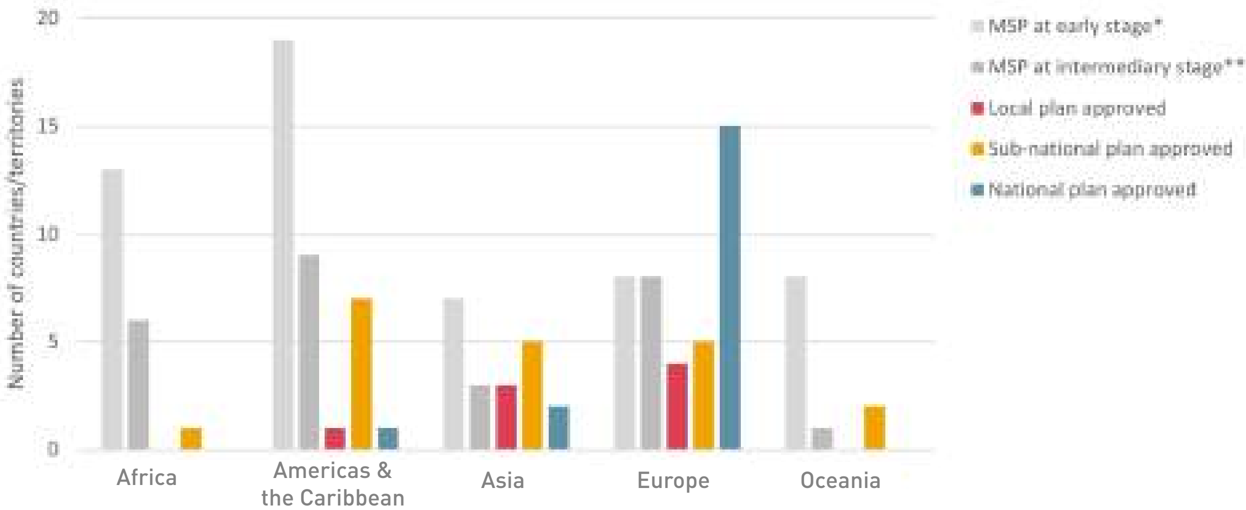

Figure 4.2. MSP around the world according to the stage of the MSP process by April 2022. *Source*: IOC-UNESCO.
*Whenever a country/territory had only pilots, it was considered at an early stage independently of its development level. **For at least part of the maritime area.
Note: Some countries were classified more than once due to the complexity of their planning systems.

Table 4.1. Application of draft typologies to a sample of approved marine spatial plans for a better understanding of the types of MSP process including commonalities and differences

Draft typology criteria (version 1.0)	Belize	Cabo Verde	Canada	Canada	Ecuador	USA	Finland	Sweden
Plan name	Belize Integrated Coastal Zone Management Plan (2016)	Management Plan for the Coastline and the adjacent Sea of the island of Boa Vista (2020)	Marine Plan Partnership for the North Pacific Coast (four plans) (2015)	Pacific North Coast Integrated Management Area (2017)	Coastal and Marine Spatial Plan (2017)	Rhode Island Ocean Special Area Management Plan (2010)	Finnish Maritime Spatial Plan 2030 (2020)	Marine spatial plans for Gulf of Bothnia, Baltic Sea and the Skagerrak/ Kattegat (2022)
Scale	Sub-national	Sub-national	Sub-national	Sub-national	National	Sub-national	National	National
Scope	Coastal zone	Coastal zone	Marine	Marine	Coastal and marine	Marine	Coastal and marine	Marine
Purpose	Comprehensive	Zoning	Comprehensive	Strategic	Strategic	Comprehensive	Strategic	Strategic
Political commitment	Executive decision?	Legal statute	Informal	Legal statute	Executive decision	Executive decision	Legal statute	Legal statute
Implementation framework	Legally binding	Legally binding	Guiding	Guiding	Guiding	?	Guiding	Guiding
Main objectives	Multiple	Multiple	Multiple	Multiple	Multiple	Economic Development	Multiple	Multiple
Spatial allocation	Detailed allocation	Partial allocation	Detailed allocation	Limited	Partial allocation	Detailed allocation	Partial allocation	Detailed allocation
Stakeholders involved	Sectors and Public	?	Sectors and Public	Sectors and Public	Limited	Sectors and Public	Sectors and Public	Sectors and Public
Participatory process	Collaborative	?	Collaborative	Collaborative	Consultative	Consultative	Collaborative	Collaborative
Funding	Government	?	Public-Private	Government	Government	Government	Government	Government

Source: IOC-UNESCO.

For the pilot StOR, eight marine spatial plans were evaluated to test the typology (Table 4.1). Some criteria could be assessed from publicly available information (e.g. scale, scope and objectives), yet others (e.g. funding, stakeholders involved, political commitment) needed background knowledge of the plan or information from competent authorities. Future applications of the criteria covering more MSP initiatives could finally examine commonalities, differences and trends among countries and regions, as well as key lessons about MSP adoption. And, as MSP evolves in the next decade, other criteria could include transboundary coherence and consultation, critical for regional cooperation in the marine space.

Going forward, to develop a regular assessment on the status of MSP globally, we propose that Member States, experts, practitioners and partners discuss and ultimately endorse typology criteria that can be used in future surveys. This typology will be very useful to synthesize survey results.

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Additional resources

- Supplementary material available online at **https://www.mspglobal2030.org/wp-content/uploads/2022/05/StOR_MSP_SupplementaryMaterial_2022-1.pdf**
- MSP around the world: **https://www.mspglobal2030.org/msp-roadmap/msp-around-the-world/**
- MSP key references: **https://www.mspglobal2030.org/resources/key-msp-references/**

Understanding the economics and the value of ocean observations

James Jolliffe and Claire Jolly

Ocean observation programmes are often supported by public expenditure in the form of research projects. But, contrary to other systems such as weather monitoring setups, long-term financing plans that sustain observing programmes and infrastructures into the future remain rare. Assessing the value and benefits of the data collected through ocean observation programmes is crucial to analysis of the appropriate form and magnitude of public expenditure that should be devoted to them (OceanObs19, 2020; Weller et al., 2019). However, existing research into the value and benefits of ocean observations data is limited and fragmented geographically.

Ocean observations sit at the base of a complex value chain (Figure 4.3). The data flowing from observations provide crucial inputs to scientific research and diverse operational services. The benefits of the data accrue from relatively local to truly global scales, from improving foundational knowledge of ecosystems to understanding ocean processes that affect the Earth's climate. The information derived from observations data is used in a range of public policy arenas and supports commercial activities, yielding new efficiencies, safety benefits and opportunities for avoiding costs.

Various studies attempt to capture the value and benefit of observations for research and operational purposes (see an overview in OECD, 2019). The societal value generated from *in situ* observations in Europe is described by the European Marine Board (2021), who report that observations cost Europe around EUR 1.5 billion per year[12] and generate an array of important yet unquantified benefits in return. Cristini et al. (2016) find a typical fixed point observatory costs around EUR 730,000 and is used to measure Essential Ocean Variables that are selected in part due to their highly beneficial uses.

Others focus on the benefits of ocean observations data to economic activity (NOAA, 2022; European Commission, 2018; Kite-Powell et al., 2008; WAGOOS and AATSE, 2006). An assessment of the contribution of earth and marine observations to Asia-Pacific economies suggests that their combined total economic value to the region in 2019 was USD 372 billion (Australian Government/Asia-Pacific Economic Cooperation, 2019). Others characterize firms providing ocean observation and forecasting technology and the intermediaries using the data to develop services (Rayner et al., 2019; Rayner et al., 2018; NOAA, 2017). A recent study of ocean observing business enterprises operating in the United States found 814 firms with 245,000 employees, accounting for USD 7.1 billion of revenue (NOAA, 2021; NOAA, 2022).

Overall, however, the costs associated with ocean observations remain difficult to summarize accurately because programmes vary in scope, technology and time frame, and quantitative evidence concerning the value of ocean observations data remains scarce. The complexity of ocean observing systems and their effects means that no single indicator is likely to become available that would accurately and succinctly summarize the value of ocean observations to society. Instead, efforts thus far have focused on improving the knowledge base surrounding the uses of ocean observations data so that the value of the benefits associated with them can be estimated.

Evidence on the use and reuse of publicly available data in ocean data repositories, and the benefits that are generated along data to information value chains, is at present particularly limited. The OECD and the Global Ocean Observing System (GOOS) are therefore exploring the data's use in society beyond the communities involved in their collection. Initial research with the UK Marine Environmental Data and Information Network suggests that the value chains associated with reuses of ocean observations data are complex and wide-ranging (Jolly et al., 2021). A recent survey of the users of public data archives in the UK revealed that ocean observations data are used in multiple areas of the economy and for many purposes. In the UK offshore wind industry, for example, data are reused to inform operations, analyse risk, validate data from other sources and inform marine planning decisions. The benefits associated with such use include productivity gains, better environmental performance and improved ocean governance.

Such studies help to outline and characterize the value chains of ocean observations data and pave the way for future assessments of the monetary value of the benefits generated. Further case studies may be conducted alongside repositories with substantial data reuse including, for example, observation data for fisheries management from the International Council for the Exploration of the Sea (ICES) or observations data assembled and harmonized by the European Marine Observation and Data Network (EMODnet). The OECD and GOOS are also working to assess the types of methodologies that would be suitable for realizing ocean observations data valuations with the objective of providing guidance to ocean observations analysts and policy-makers. Such studies and others on the costs

12 The cost data in European Marine Board (2021) are taken from the Inception Impact Assessment for the European Commission's Ocean Observation – Sharing Responsibility Initiative (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12539-Ocean-Observation).

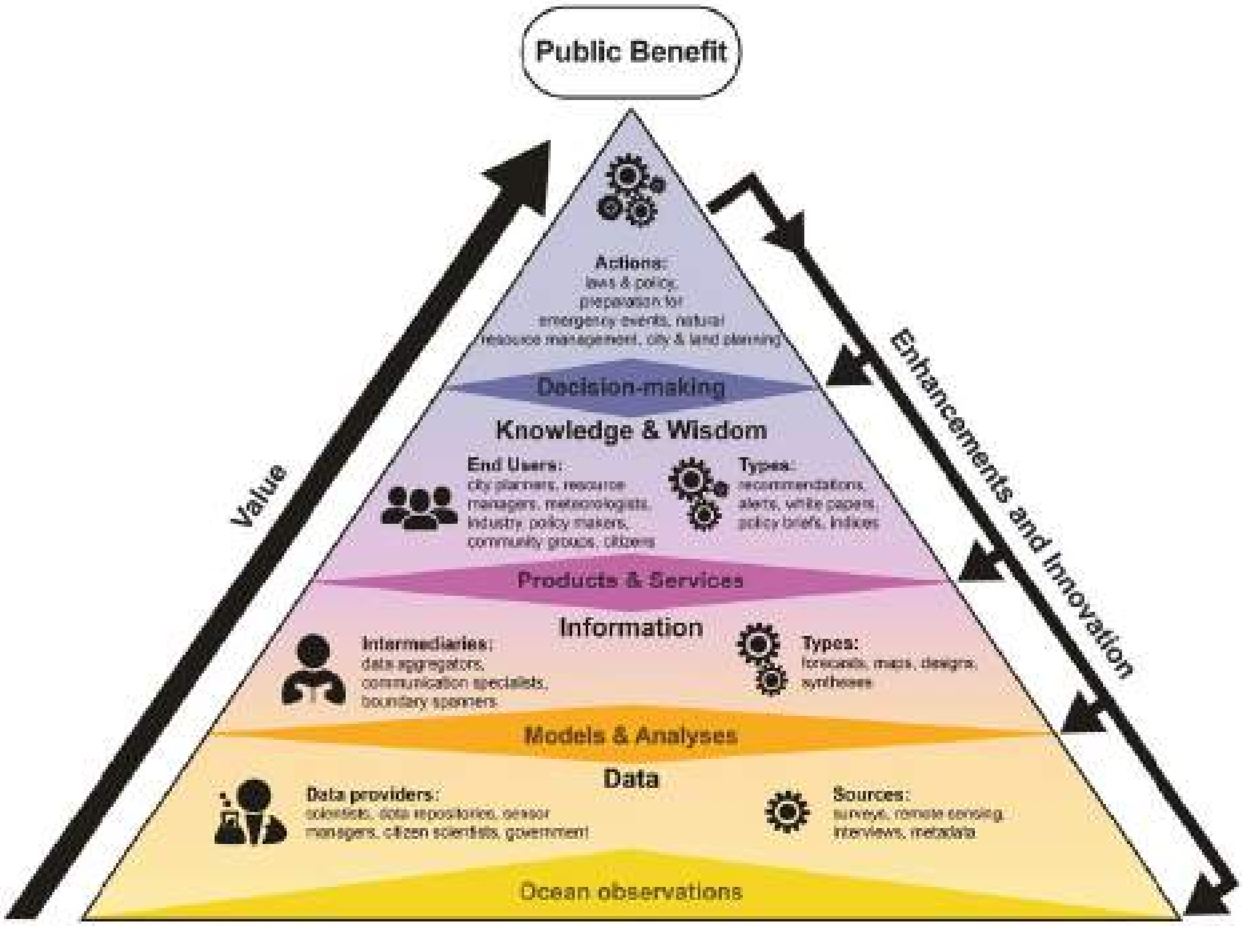

Figure 4.3. Ocean observation value chain: From ocean observations to public benefit. *Source:* European Marine Board, 2021 (CC BY 4.0); adapated from Virapongse, et al., 2021 (CC BY 4.0).

and benefits of ocean observations are essential and will contribute indispensable evidence on the value of ocean observations data to society.

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Challenge 5.
Unlock ocean-based solutions to climate change

Enhance understanding of the ocean-climate nexus and generate knowledge and solutions to mitigate, adapt and build resilience to the effects of climate change across all geographies and at all scales, and to improve services including predictions for the ocean, climate and weather.

Coastal blue carbon ecosystems

Chenae Neilson and Elisabetta Bonotto on behalf of Coordinator Team of the International Partnership for Blue Carbon

Of the land, atmosphere and ocean components of the global carbon cycle that exchange carbon on timescales of decades to centuries, the ocean contains more than 90% of the carbon contained in these reservoirs (Sarmiento and Gruber, 2002). This includes coastal ecosystems such as mangroves, salt marshes and seagrasses that sequester and store significant 'blue carbon'. Coastal blue carbon ecosystems are hotspots for carbon storage, with the intensity of soil carbon sequestration rates per hectare up to ten times larger than those of terrestrial ecosystems (McLeod et al., 2011).

Coastal blue carbon ecosystems are recognized for their role in mitigating climate change, while achieving significant co-benefits, such as coastal protection from storms, improving water quality, benefiting biodiversity, fisheries, food security, tourism, and providing livelihoods for many coastal communities.

Despite their importance, coastal blue carbon ecosystems are some of the most threatened ecosystems globally. Pressures from overextraction, urban and industrial coastal development, pollution, and pressures from agriculture and aquaculture are some of the common causes of coastal ecosystem damage and destruction.

When blue carbon ecosystems are damaged, e.g. due to vegetation loss or hydrology changes related to agriculture, sediments, and the carbon within them, could be oxidized, releasing CO_2 into the atmosphere and ocean. Consequently, when degraded or destroyed, these ecosystems emit the stored carbon into the atmosphere and ocean and become sources of greenhouse gas, as efficient as they were being a carbon sink.

However, studies estimate that with improved management and intervention, the total potential contribution from coastal and marine ecosystems to climate mitigation is between 0.50 and 1.38 $GtCO_2$ e/year by 2050. More specifically, for mangroves this is between 0.18–0.29 $GtCO_2$ e/year, for salt marsh 0.05–0.10 $GtCO_2$ e/year and for seagrass 0.22–0.77 $GtCO_2$ e/year (Hoegh-Guldberg et al., 2019). This mitigation potential accounts for ~12% of all ocean-based actions (Figure 5.1).

Global data available on extent varies for each ecosystem type. For example, while mangroves are relatively well mapped, the global extent of salt marshes and seagrass meadows are under-documented. Nevertheless, the total global area of mangroves is estimated to cover 13.59 million hectares (Mha) (Spalding and Leal, 2021), salt marsh cover is estimated at 5.49 Mha (McOwen et al., 2017) and seagrass estimates range between 16.03 and 26.65 Mha (McKenzie et al., 2020; Hoegh-Guldberg et al., 2019). Together, these ecosystems cover approximately 40.42 Mha and are found along the coastline of every continent (Figure 5.2).

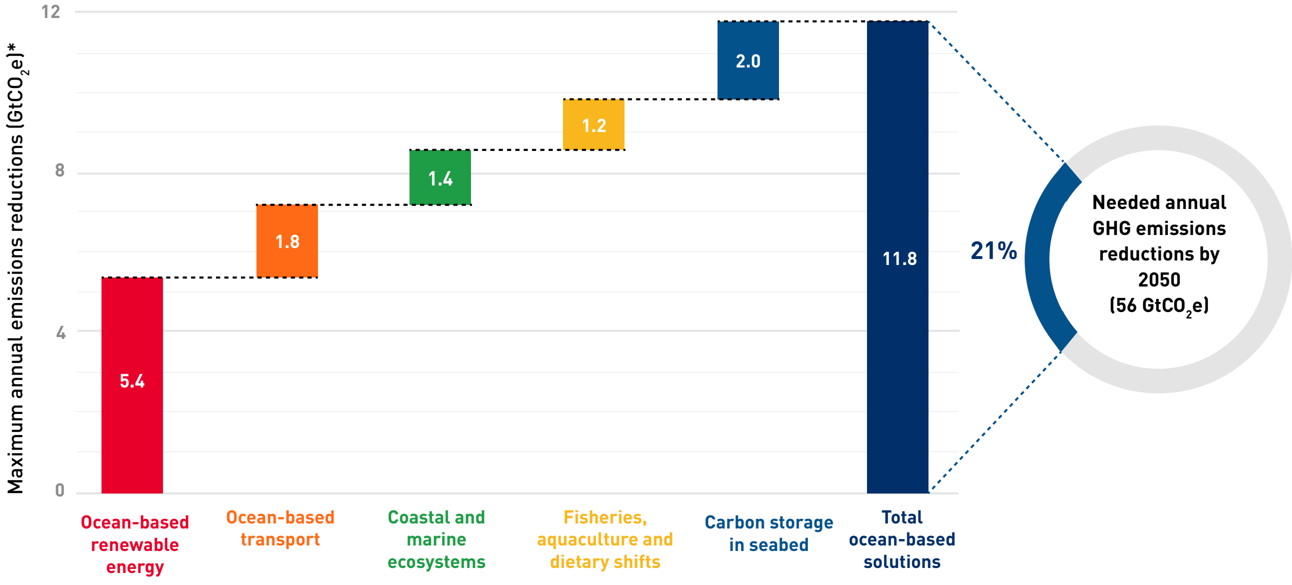

Figure 5.1. Potential contribution of five areas of ocean-based action to mitigating climate change in 2050 (maximum $GtCO_2e$). *Source:* Hoegh-Guldberg et. al, 2019, © World Resources Institute.

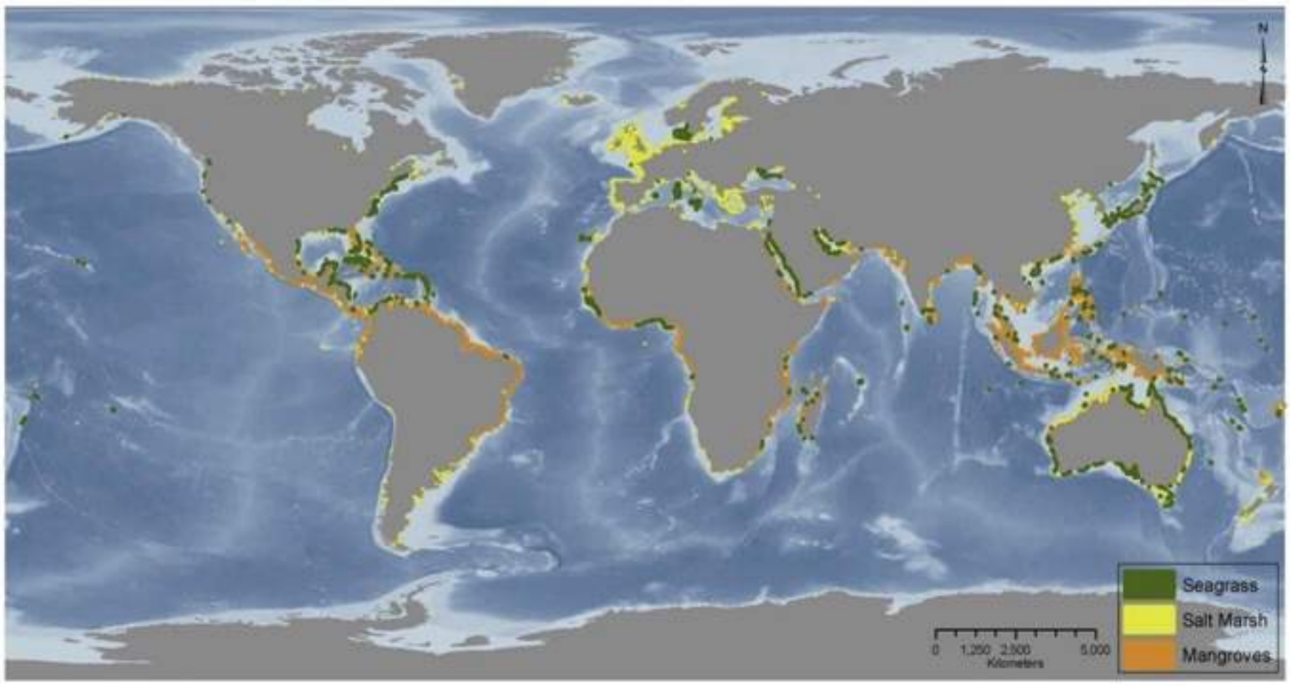

Figure 5.2. Overview of the global distribution of mangroves, saltmarshes and seagrasses. *Source:* United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) datasets.

Although the historical extent of the ecosystems is difficult to determine due to losses that occurred before mapping was possible, it is estimated that 20-50% of global blue carbon ecosystems have already been lost or degraded (Hoegh-Guldberg et al., 2019).

Rates of loss based on current estimates

- Mangroves are being lost at a rate of between 0.11–0.13% annually marking a significant reduction in earlier estimates of global loss rates worldwide (Spalding and Leal, 2021). However, loss rates are still high in many countries including Indonesia, Myanmar, Malaysia, the Philippines, Thailand and Viet Nam (Goldberg et al., 2020).
- Tidal marshes are being lost at a rate of 1.0–2.0% annually (Pendleton et al., 2012).
- Seagrasses are being lost at a rate of 2.0–7.0% annually, mainly due to pollution of coastal waters and destructive fishing practices (Turschwell et al., 2021).

Table 5.1. Global extent and loss rates of coastal blue carbon ecosystems.

Ecosystem	Area cover (km^2)	Area cover (million ha)	Approx. rates of loss (% per year)
Mangroves	136,000	13.6	0.11—0.13
Salt marsh	55,000	5.5	1—2
Seagrass	325,000	16.03—32.5	2—7

Source: Adapted from Hoegh-Guldberg et al., 2019.

Actions that contribute to climate mitigation include activities that result in reduced emissions or increased removals. In the case of nature-based solutions, which include coastal ecosystems, this can be achieved through the following:

1. Ecosystem protection and management: Activities that reduce the destruction and degradation of blue carbon ecosystems avoid emissions by keeping the carbon that is currently stored in soils and vegetation stable and undisturbed.

2. Ecosystem restoration: Restoring vegetation and hydrology in blue carbon systems can re-establish natural sequestration, removing CO_2 from the atmosphere.

Efforts to conserve and restore coastal blue carbon ecosystems are growing, but currently remain relatively small-scale. Notably, efforts to protect mangroves have risen globally, with an estimated 42% of all remaining mangroves now in designated protected areas (Spalding and Leal, 2021). This compares to only about 1.5% of the combined blue carbon ecosystems in marine protected areas (Zhao et al., 2020).

The potential for climate change mitigation and adaptation through nature-based solutions was acknowledged in the *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (Pörtner et al., 2019), which recognizes that improved protection and management of coastal blue carbon ecosystems can reduce carbon emissions by up to 2% of current total carbon emissions (Bindoff et al., 2019), and could provide climate change mitigation through increased carbon uptake and storage by around 0.5% of current global emissions annually. It also acknowledges the multiple important benefits healthy blue carbon ecosystems support, such as providing storm protection, improving water quality, and benefiting biodiversity, fisheries, food security, tourism and livelihoods of local communities.

Further research areas

- Understanding how climate change affects carbon stocks and accumulation rates in mature blue carbon ecosystems and during their restoration.
- Improving the estimates of carbon storage and greenhouse gas fluxes within coastal ecosystems to reduce current uncertainties around measurement, reporting and verification (IPCC, 2019).
- Development of improved and globally applicable approaches to assess the extent of blue carbon ecosystems, net greenhouse gas potential.
- Improving tools for measuring, modelling and valuing wider ecosystem services.
- Improving estimated carbon impacts of management actions (Macreadie et al., 2019).
- Understanding the social and economic contexts that support successful conservation and restoration of blue carbon ecosystems (Stewart-Sinclair et al., 2020).

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Challenge 6.
Increase community resilience to ocean hazards

Enhance multi-hazard early warning services for all geophysical, ecological, biological, weather, climate and anthropogenic related ocean and coastal hazards, and mainstream community preparedness and resilience.

Sea level rise

Anny Cazenave and Gary Mitchum

Sea level is one of the best indicators of climate change because it is an integrated, and therefore robust, variable. This is because sea level change results from changes occurring in the ocean's mass and density fields. These changes in the mass and density fields are happening in response to forced, as well as unforced, climate variability, through mechanisms such as ocean warming, the melting of grounded ice and changes in landwater storage. Sea levels have been monitored by tide gauges since the late eighteenth century and by tide gauges and satellite altimeters since the early 1990s. Most recent sea level reconstructions based on the tide gauge data indicate that the global mean sea level rose by 12 +/- 5 cm between 1901 and 1990, with a mean rate of rise of 1.3 +/- 0.6 mm/year over the period (Oppenheimer et al., 2019; Figure 6.1).

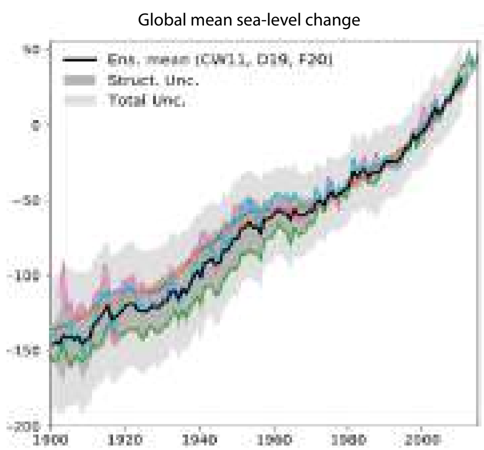

Figure 6.1. Sea level reconstructions from 1900 by different authors; green: Church and White, 2011; pink and orange: Dangendorf et al., 2017, 2019; blue: Hay, 2015; black: ensemble mean. *Source:* Palmer et al., 2021.

Studies in the altimeter era have shown that the global mean sea level rise rate has accelerated (Nerem et al., 2018; WCRP, 2018). The global mean sea level rise rate as observed by satellite altimeters has increased from 2.1 mm/year over 1993–2002 to 4.7 mm/year over 2013–2021 (Figure 6.2).

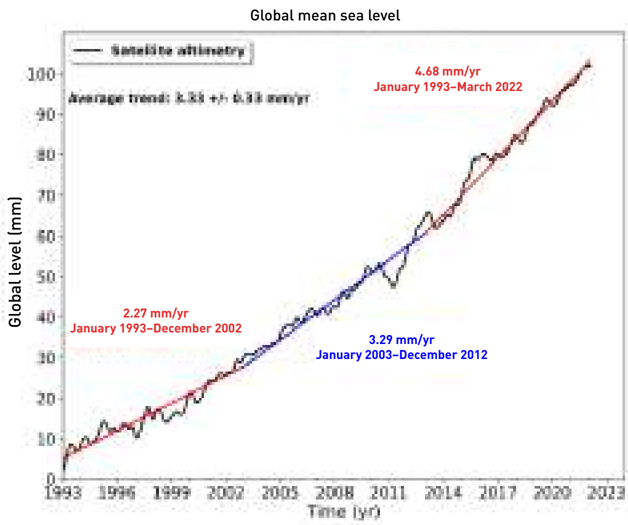

Figure 6.2. Global mean sea level rise from satellite altimetry from January 1993 to March 2022 (black curve). The red and blue straight lines indicate successive global mean sea level trends. Altimetry data from AVISO https://www.aviso.altimetry.fr *Source:* Cazenave and Moreira, 2022.

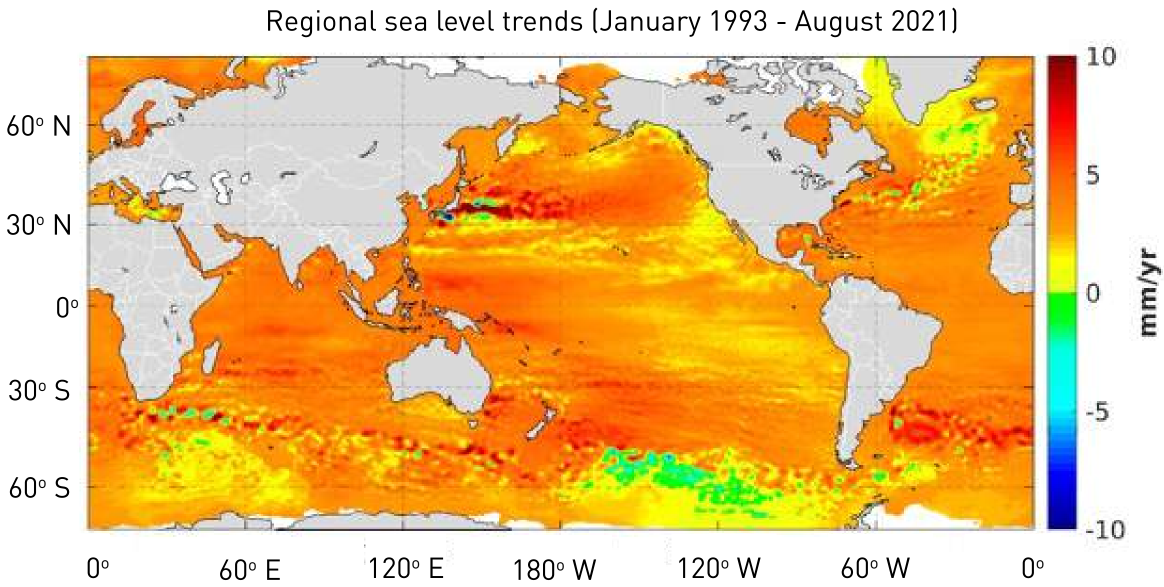

Figure 6.3. Regional sea level trends from January 1993 to August 2021, based on multimission satellite altimetry, with the global mean trend of 3.3 mm/yr included. *Source:* Copernicus Climate Change Service https://www.climate.copernicus.eu.

Studies based on tide gauges have shown that this acceleration has been happening from an even earlier period – at least since the late 1960s (e.g. Dangendorf et al., 2019; IPCC, 2019). The primary cause of the contemporary global mean sea level rise is the increase in ocean thermal expansion and the melting of grounded ice (glaciers, Greenland and Antarctica). These factors contribute 46% and 44%, respectively (IPCC, 2019). The remaining 10% of the increase is attributed to changes in terrestrial water storage. The trends measured by satellite altimeters show that the sea level rise is not geographically uniform (Figure 6.3).

Figure 6.4. Current status of the *in situ* GLOSS core network of tide gauges at the Permanent Service for Mean Sea Level (PSMSL). *Source*: Holgate et al., 2013.

The observed spatial pattern in the sea level trends results from the superposition of 'fingerprints' caused by different processes. In addition to the global mean change, there are contributions due to spatial changes in seawater density, atmospheric loading, as well as deformations of the solid Earth and the associated gravitational changes in response to mass redistributions caused by past and present-day land ice melt. At present, non-uniform ocean thermal expansion dominates all other processes (IPCC, 2019). At local scales, however, additional small-scale processes (e.g. shelf currents, trends in waves, freshwater input to estuaries) superimpose on the global mean and regional sea level changes, resulting in coastal sea level trends that can substantially deviate from adjacent open ocean sea level changes. In addition to these ocean dynamical changes, vertical land motion due to groundwater and hydrocarbon extraction, land-use changes and urbanization are additional forcing factors that can significantly modify sea level variations in the coastal zone. Unlike the global mean and regional sea levels routinely measured by satellite altimetry, coastal sea level changes remain an observational challenge. Coastlines are undersampled by tide gauges in most regions and while the IOC's Global Sea Level Observing System (GLOSS) core network of ~300 tide gauge stations has been selected to be globally representative, maintaining the operational status of these is a challenge exemplified by the African continent (Figure 6.4).

Our coastlines are currently inaccessible (within 15 km of the coast) by conventional altimetry missions. Sea level rise, possibly up to 1 m by 2100 (IPCC, 2019), when combined with extreme events (Pelling et al., 2013, is a major threat to the highly populated, low-lying coastal regions where more than 10% of the world's population lives. The challenge in the coming years is to improve the space-based and *in situ* observing systems for monitoring coastal sea level rise. This includes increased coverage of the current tide gauge network with GNSS observations to estimate land motion as well as deploying advanced altimeter systems (e.g. SAR altimetry) that will provide high-resolution sea level measurements in the coastal zone. Quantitative understanding of the physical mechanisms causing coastal sea level changes, either based on *in situ* measurements from coastal observatories or from high-resolution modelling (or preferably from both) is another major challenge that should be addressed in parallel. These efforts will support the production of improved sea level change projections that will benefit coastal zone management efforts around the globe.

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Storm surges and tsunamis – Coastal hazards without borders

Bernardo Aliaga, Rick Bailey, Bruce M. Howe, Srinivasa Kumar Tummala and Yong Wei

Globally, around 10% of our population and physical assets are situated less than 10 m above sea level. Many coastal cities are directly affected by severe weather, climate and ocean-driven impacts, such as tsunamis and storm surges. These impacts will increase due to sea-level rise caused by anthropogenic climate change (Swain et al, 2020).

Tsunamis are primarily generated by large undersea earthquakes along subduction zones and can be by far the most destructive coastal hazard. Recent devastating examples include the 2004 Indian Ocean tsunami, which claimed more than 230,000 lives across a number of countries. Smaller but still dangerous tsunamis can be generated by submarine landslides (e.g. the 2018 Palau tsunami) and volcano collapses (e.g. the 2018 Anak Krakatau event). Some of these non-seismic-generated tsunami events can also create basin-wide tsunamis, as demonstrated by the recent Hunga Tonga-Hunga Ha'apai volcanic eruption on 15 January 2022. Storm surges can devastate low-lying coastlines, as was the case in 2005 when Hurricane Katrina resulted in 1,800 fatalities and damage totalling USD 125 billion.

Tropical cyclones and storm surges are monitored by a variety of meteorological services and warning centres. Ten of these warning centres worldwide are designated as either a Regional Specialized Meteorological Centre or a Tropical Cyclone Warning Centre by the World Meteorological Organization (WMO). Observing systems include infrared images from weather satellites, land-based Doppler radar, perturbations in Global Positioning Signals (GPS), reconnaissance flights, etc. The forecast of storm surges has advanced from regional/basin-wide, two-dimensional model hindcasts to global, data-driven efforts and real-time flooding simulation assisted by three-dimensional models.

The global tsunami warning and mitigation system developed by the Intergovernmental Oceanographic Commission of UNESCO (IOC) comprises a network of twelve Tsunami Service Providers (TSPs) in different ocean basins, which provide tsunami forecast information to National Tsunami Warning Centres (Figure 6.5). Tsunamis are monitored through extensive networks of seismic and sea level observing systems, delivering near real-time data through multiple channels. Major exercises are routinely held in each ocean basin to test warning systems and community preparedness.

The accuracy of forecasting storm surges or tsunami events is heavily dependent on the monitoring systems. Greater utilization of existing and new observing technologies, such as the Global Navigation Satellite System (GNSS), global high-resolution bathymetry, sea-floor cabled observatories, satellite altimetry, ocean bottom seismometers, etc., are opening up new avenues to monitor land and ocean processes that can lead to better detection, monitoring and forecasting of tsunamis and storm surges (Angove et al., 2019). An international joint task force is pioneering subsea SMART (Science Monitoring And Reliable Telecommunications) cables, where ocean bottom temperature, pressure and seismic acceleration sensors are integrated into the repeaters of commercial telecommunication cable systems (Howe et al., 2019).

While an accurate forecast and early warning system plays a crucial role in mitigating losses due to coastal hazards, public awareness and preparedness play an equally important role. Community-based recognition programmes, such as the IOC-UNESCO Tsunami Ready Programme, help enhance the preparedness of coastal communities in responding effectively to coastal hazards.

The UN Decade of Ocean Science for Sustainable Development (2021–2030) is an opportunity to enhance the timeliness and accuracy of tsunami warnings for 100% of at-risk coastal communities, ensuring that they are 'tsunami-ready', and thereby contributing towards the 'Safe ocean' Decade Outcome.

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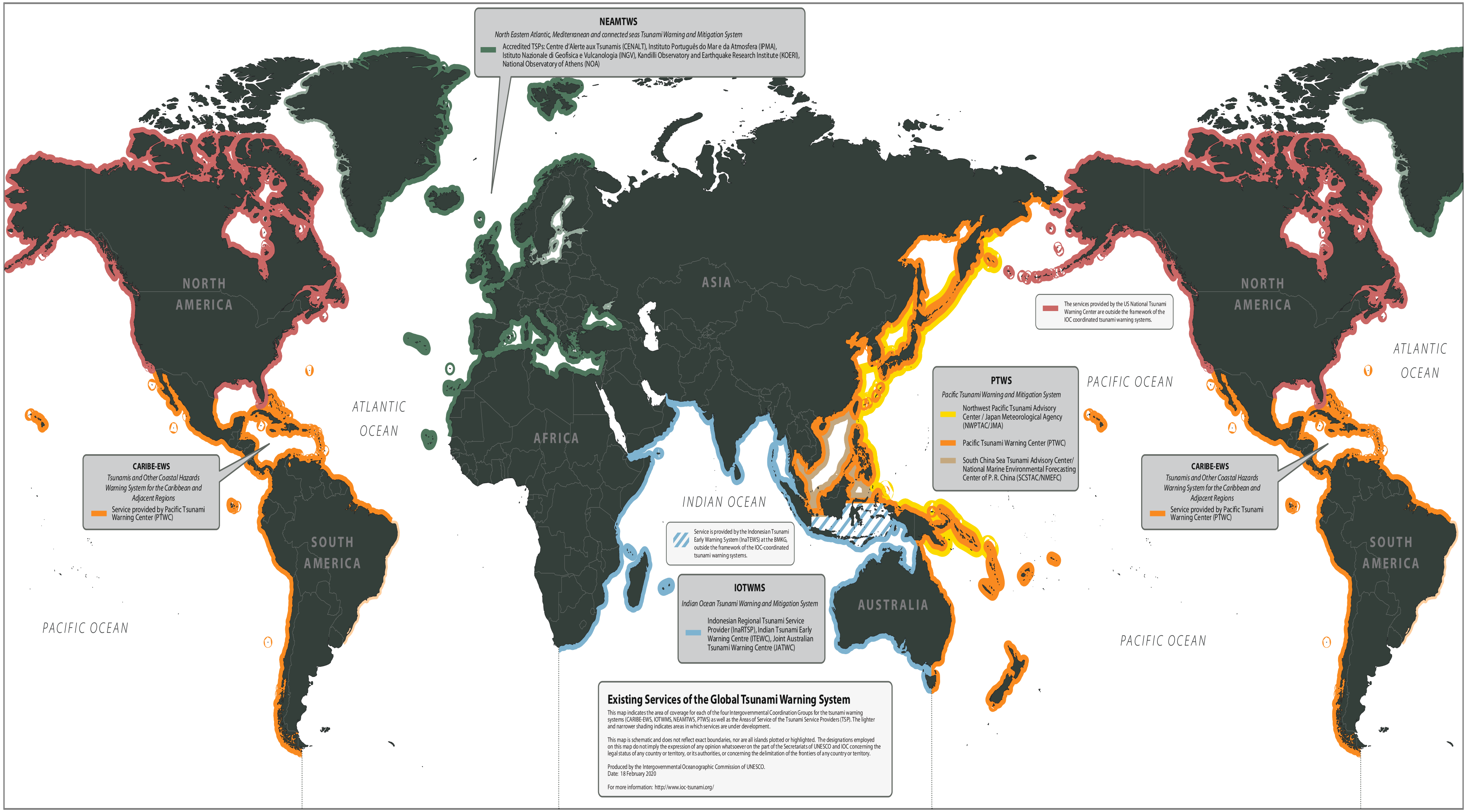

Figure 6.5. Global coverage of Tsunami Warning Centres under IOC-UNESCO. *Source*: IOC-UNESCO.

Observing and predicting the global coastal ocean

Nadia Pinardi, Vassiliki Kourafalou, Joaquín Tintoré, Emma Heslop and Mairead O'Donovan

Coastal areas are where most of the world's population lives and where the response to the UN Decade's challenges will have the largest impact. The concept of the 'global coastal ocean' is transformational (Robinson and Brink, 2006), as it highlights the phenomena that control how land and offshore ocean waters interact to create a complex system, strongly impacted by human activities on both local and global levels. Coastline geometries produce the sea level response to multiple forcing factors and regulate the deep ocean circulation through the dissipation of energy on the shelf (Woodworth et al., 2019; Wunsch and Ferrari, 2004). Thus the global coastal ocean contains processes that are key for the ocean climate.

Thanks to the advent of optical satellite monitoring, a first global assessment of the state of the world's beaches – in particular their rates of shoreline changes – has been produced, showing large changes everywhere, mainly loss of beaches from 1984 to 2017 (Luijendijk et al., 2018). The challenge is to improve such assessment with the help of *in situ* observing that will increase the satellite monitoring capacity.

A key global coastal ocean *in situ* monitoring infrastructure is provided by tide gauges that measure the rate of relative sea level rise for the past several decades up to centuries. New sensors for wetlands and low-lying coastal areas such as smart sea level sensors (SSLSs) provide a future opportunity to aid in emergency planning and response and will produce an important dataset for scientists, engineers and regional planners in quantifying the short- and long-term risks associated with continued sea level rise (Cobb et al., 2020).

Real-world events provide poignant examples of the need to advance forecasting for coastal areas. One such case is that of extreme sea level forecasting in Venice, where multi-billion euro funding has been invested in the city's flood defence barriers. The successful operation of these flood defence systems requires a forecast lead time of 2–3 days and an error of less than 10 cm. Recent events that clearly illustrated the need to improve forecasting capabilities happened in 2019, when there was a 20% error in forecasting (Figure 6.6; von Schuckmann et al., 2021) and in 2020 when the forecast was delivered with an error of 10–15%, less than 24 hours in advance. In both cases, the simple tidal forecast was insufficient, the high sea level occurred during a relatively low tidal amplitude peak (Figure 6.6), and the barrier defence system was not activated. This resulted in repair costs running into millions of euros for cultural heritage sites and significant damage to the local economy.

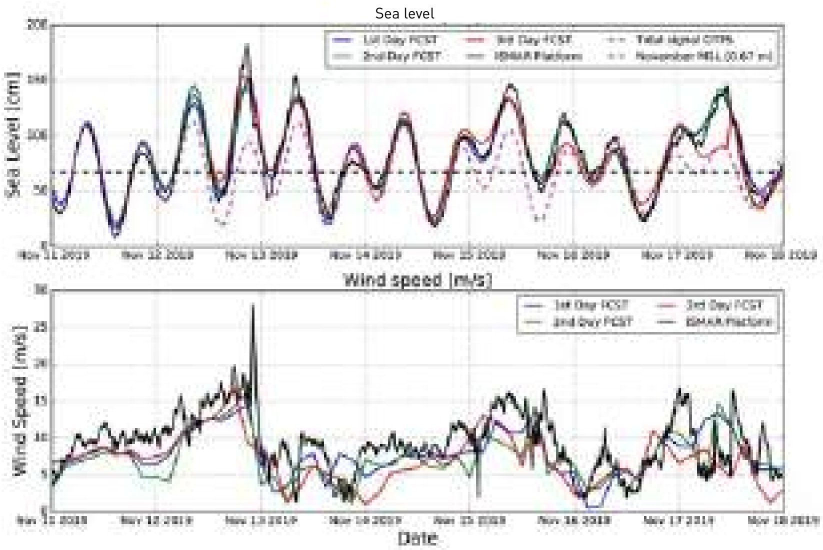

Figure 6.6. Analysis of the sea level forecast error for the Venice 'acqua alta' event of 12 November 2019. The top figure represents the sea level forecast at the start of each day from November 10 to November 18 and concatenated to make a time series. The black line shows the measured sea level at a station just offshore the Venice Lagoon. The black dashed line shows the mean sea level for November at the station. The blue, green and red lines show the forecast while the dashed purple line shows the tidal signal only. On 12 November 2019 around 22.00 UTC, the difference between the measured sea level and the forecast is about 35 cm, i.e. an error of around 20%. The bottom panel shows the comparison between measured winds and the European Centre for Medium range Weather Forecasts (ECMWF) forecast winds used to force the ocean model forecast. The high wind measured is not well reproduced by the ECMWF winds, one of the potential causes of the forecast error. *Source:* von Schuckmann et al., 2021.

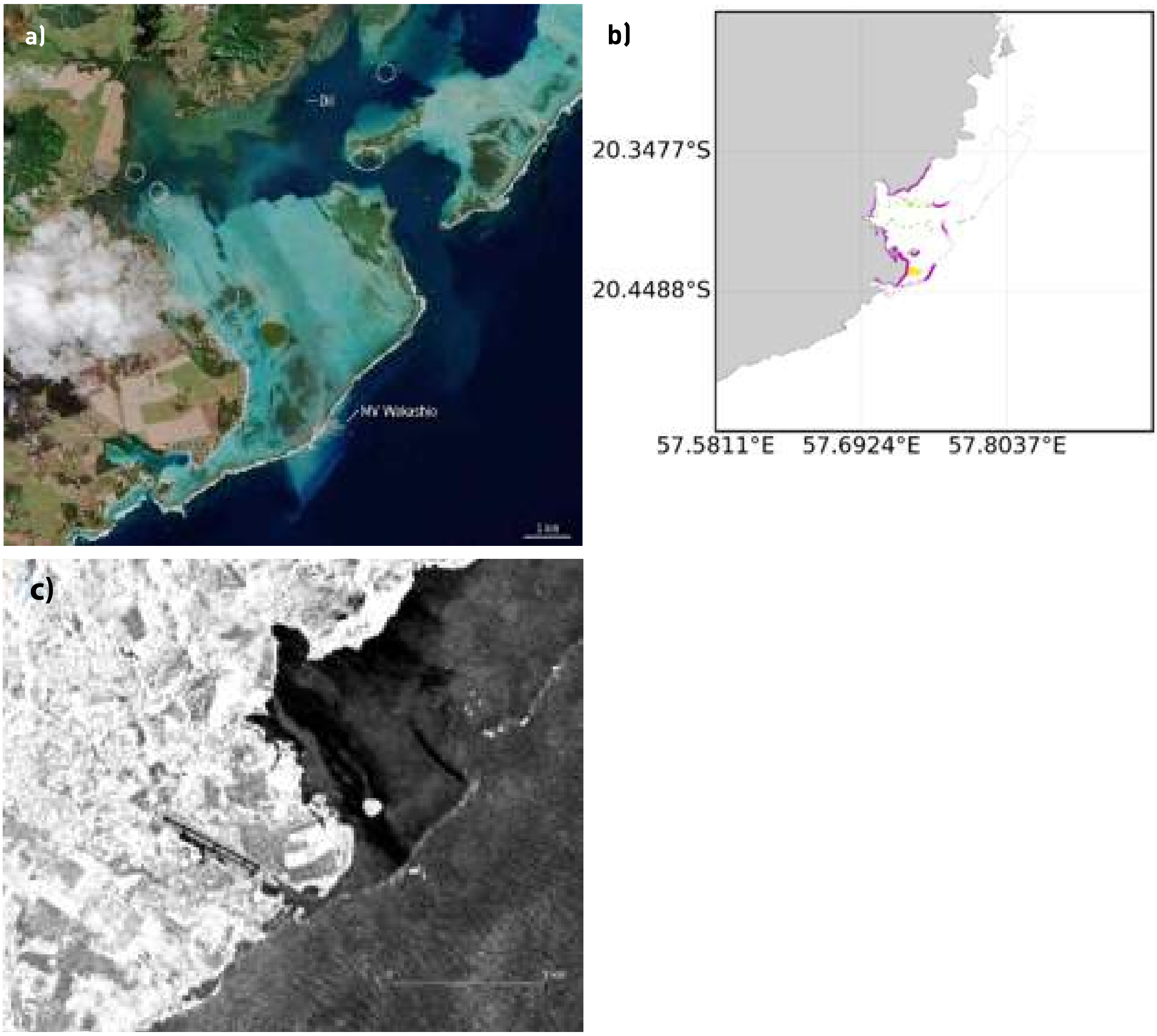

Figure 6.7. a) Sentinel-2 image of the MV Wakashio accident near the Mauritius island coastlines on 11 August 2020. *Source*: ESA; **b)** forecasted sea surface oil concentrations and contaminated coastal segments (marked by purple dots) for the 10/08/2020 00.00 UTC (left panel) and **c)** Copernicus Sentinel-1 SAR imagery for the same date at 01.37 UTC (right panel). Darker areas on the right panel indicate the presence of oil. *Source:* Sepp Neves et al., 2020.

Operational forecasting of hazardous pollution dispersal is another example that highlights the requirement for standardized, widely replicable forecasting systems for the coastal ocean (De Dominicis et al., 2014). The impacts of the Wakahsio oil spill accident off Mauritius island in 2020 were mitigated and managed effectively due to real-time forecasting (Figure 6.7; Sepp Neves et al., 2020). While the capability and expertise exist to help limit damage to coastal environments, it is often concentrated in remote locations requiring relocatable systems. Local capacity needs to be improved so that vulnerable regions and communities can develop capabilities for real-time coastal forecasting and disaster risk reduction.

Improvements of global and basin-scale operational ocean forecasting have made information openly and freely available at kilometric scales (Le Traon et al., 2019; Pinardi et al., 2019) and these capabilities enable the design of integrated observing and forecasting systems for coastal areas (Korafalou et al., 2015), for example in the Mediterranean (Tintoré et al., 2019). However, we need to consolidate standards and best practices (Pearlman et al., 2019) to replicate integrated systems (Révelard et al., 2022), with standards and services that can inform sound and sustainable coastal management practices.

The expertise exists but is scattered in silos. The Ocean Decade aims to optimize capability and capacity widely and equitably, and to develop the delivery of advanced services for the global coastal ocean, in support of all Ocean Decade challenges.

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Additional resources

- Coastpredict programme **https://www.coastpredict.org/**
- Copernicus **https://marine.copernicus.eu/**

Harmful algal bloom impacts increase amid rising seafood demand and coastal development

Gustaaf M. Hallegraeff, Adriana Zingone and Henrik Enevoldsen

Among the approximately 10,000 species of marine phytoplankton in the world's oceans today, some 200 taxa produce toxins that can threaten seafood security and human health, cause wild or aquaculture fish-kills and interfere with recreational use of coastal waters and tourism. Non-toxic microalgae attaining high biomass can also cause harmful algal blooms (HABs) by producing seawater discolorations, anoxia or mucilage that negatively affect the environment and human activities, with consequences for well-being and the economy.

Several studies in recent decades have suggested an ongoing expansion, intensification and increased impact of HABs, with evidence from a number of cases that have gained high prominence in the scientific world and in society. Eutrophication, human-induced introduction of alien harmful species, climatic variability and aquaculture have all been mentioned as possible causes of HAB trends at various spatial and temporal scales. However, the lack of a synthesis of the relevant data has hampered a sound global assessment of the present status of phenomena related to harmful algae.

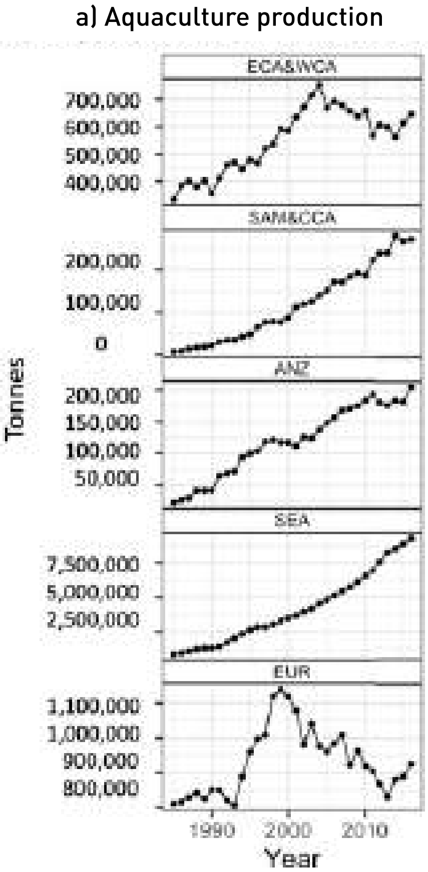
The IOC-ICES-IAEA Global HAB Status Report (GHSR) (Hallegraeff et al., 2021*a*; Hallegraf 2021b; Zingone et al., 2021a), supported by the Government of Flanders and hosted within the IOC-IODE, compiled the first overview of Harmful Algal Bloom events and their societal impacts. GHSR was based on the expansion and analysis of two databases, OBIS (Ocean Biodiversity Information System)/HABMAP (tracing the distribution of potentially toxic species based on published literature), and HAEDAT (Harmful Algal Event Database) collecting events produced by toxic or non-toxic species that exert an actual impact on human health or activities, or on the environment (Zingone et al., 2021*b*). The Harmful Algal Information System (HAIS) mapping tool allows for any combination of species occurrence (OBIS/HABMAP) and event data (HAEDAT) (Figure 6.8).

Figure 6.8. World map of distribution events associated with paralytic shellfish toxins (red) combined with that of the occurrence of *Alexandrium* causative organisms (blue). *Source:* based on data obtained from the HAIS Data Portal https://data.hais.ioc-unesco.org/.

Regional overviews compiled by 109 scientists from 35 countries based on those databases have highlighted the widespread occurrence and the variegated nature of HABs, whose causative species show different types of impacts, spatial/temporal ranges and ecological characteristics, as well as highly variable responses to environmental changes, including climate change.

Further, the first global scale statistical analyses of HAEDAT (9,503 events in the period 1985–2018) and using the OBIS phytoplankton dataset (5,944,392 microalgal records including 289,668 distribution records of harmful species) as a proxy for observational efforts, revealed the lack of any uniform global trend in the number of harmful algal events once data were adjusted for regional variations in observational activities. Trends were instead variable and contrasting among different regions, which were characterized by different types of events, harmful species and emerging impacts. Because of the diversity of HAB events and the complexity of coastal areas, climate change and eutrophication impacts vary from place to place. Thus, trends and patterns of these phenomena and their links to multiple climatic or anthropogenic drivers should be analysed at the local and regional scale, with a focus on species-specific ecological characteristics of the blooms.

Using a FAO dataset on aquaculture, a clear relationship ($r=0.43$, $z=3.59$, $p=0.0003$) was found between the trends of harmful algal events and the monitoring effort associated with the development of aquaculture operations in coastal areas (Hallegraeff et al., 2021*b*) (Figure 6.9), leading to the conclusion that the latter is the source of the perceived increase in harmful algae events, while there is no empirical support for broad statements regarding increasing global trends. The link observed between aquaculture-driven monitoring and HAB trends indicates that the exploitation of marine resources will increasingly face harmful algal blooms, highlighting the need to forecast and manage them in order to minimize their impacts.



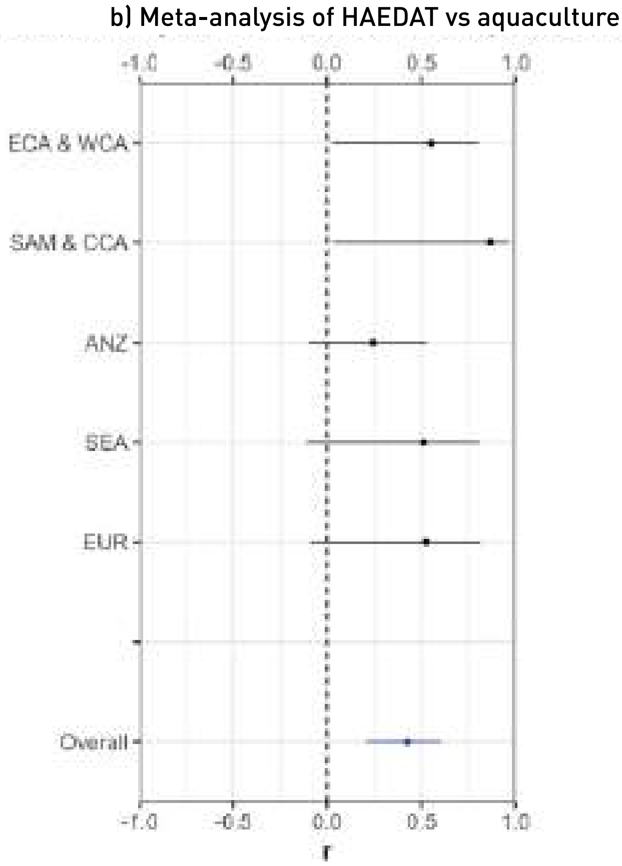


Figure 6.9. Relationship between changes in aquaculture production and harmful algal bloom events recorded in HAEDAT in the period 1985–2018. **a)** Changes in five regions (East and West Coast America; South America, Central America, Caribbean; Australia and New Zealand; South-East Asia; Europe) of tonnage of aquaculture production of fish, molluscs, crustaceans and aquatic plants; and **b)** Meta-analysis of HAEDAT events over time vs aquaculture. Weighted mean correlations (filled circles) are shown with 99% confidence limits (bars). The overall number of HAEDAT events over time was significantly correlated with aquaculture production (bottom), as seen from the confidence bar limit above the 0 value line. *Source:* Harmful Algal Events Database; Hallegraeff et al. 2021*b*

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Additional resources

- IOC-UNESCO Harmful Algae Information System **https://data.hais.ioc-unesco.org**
- OBIS **https://www.obis.org**

Challenge 7. Expand the Global Ocean Observing System

Ensure a sustainable ocean observing system across all ocean basins that delivers accessible, timely and actionable data and information to all users.

Progress and challenges of the *in situ* Global Ocean Observing System

Emma Heslop, Mathieu Belbeoch, Ward Appeltans and Serita van der Wal

The Global Ocean Observing System (GOOS) continues to expand its capabilities to deliver integrated multidisciplinary ocean information in support of monitoring and predicting our changing climate, ocean health, ocean life, weather and hazard warnings. However, the system is at risk due to short-term funding and pandemic-related constraints.

The *in situ* GOOS now numbers 8,208 ocean observing platforms registered at OceanOPS (Figure 7.1) across 12 global ocean observing networks, with some 84 countries contributing. There are also 12 developing BioEco ocean observing networks. This GOOS supplies essential data and products to communities, and to weather, climate and ocean forecasters to support the safety of life and property at sea, maritime commerce, sustainable fisheries and the well-being of coastal communities. It is also foundational for monitoring long-term climate change and the increasing stress on the ocean from human activities. Teeming with abundant life, the ocean is an important source of food and livelihoods, with over 3 billion people in the world depending on it.

During the last five years, new 'emerging' networks around underwater gliders, coastal ocean radars, and even sensors mounted on marine animals were incorporated into GOOS, and routinely deliver data to global and regional users. Besides delivering essential ocean data in remote locations – which is important for global weather forecasts and oceanographic research – some networks such as AniBOS use these sensors to understand animal behaviour for conservation.

Through a study published in *Frontiers in Marine Science* (Satterthwaite et al., 2019), GOOS and its partners have recently identified significant knowledge gaps on the status of marine life. The study reveals that the coverage of sustained biological observations only represents 7% of the entire ocean surface. The open ocean and some parts of the South American, Eastern European, Asian, Oceania and African coasts were especially under-represented. The results are alarming, as they suggest that the lack of information is often greatest where it is needed the most: in areas of high biodiversity with intense human pressures. The study will allow GOOS to take prioritized action.

During the pandemic, the global system showed initial resilience to the impacts of COVID-19, due to its increasingly autonomous capabilities and diversity of platforms for ocean observing. However, multiple long-term buoy data sets, research-vessel-based reference measurements and ocean carbon observations will forever have a gap during the pandemic period, and many of these systems will not return to pre-pandemic data reporting levels for some time yet. Large area gaps in coverage of Argo floats and drifters, together with maintenance of the Tropical Moored Array in the Indian Ocean, due to constraints on research vessel operations, must also be addressed.

Increasing societal needs for ocean data, such as for adaptation to climate change in the coastal zone, extreme storm predictions, ocean biodiversity loss, and the need to address food security and the potential for renewable energy from the ocean would benefit from expanding current observing systems. This should be done through the development of a truly transdisciplinary infrastructure, where current platforms are upgraded with additional sensors (e.g. biogeochemical or marine weather), and

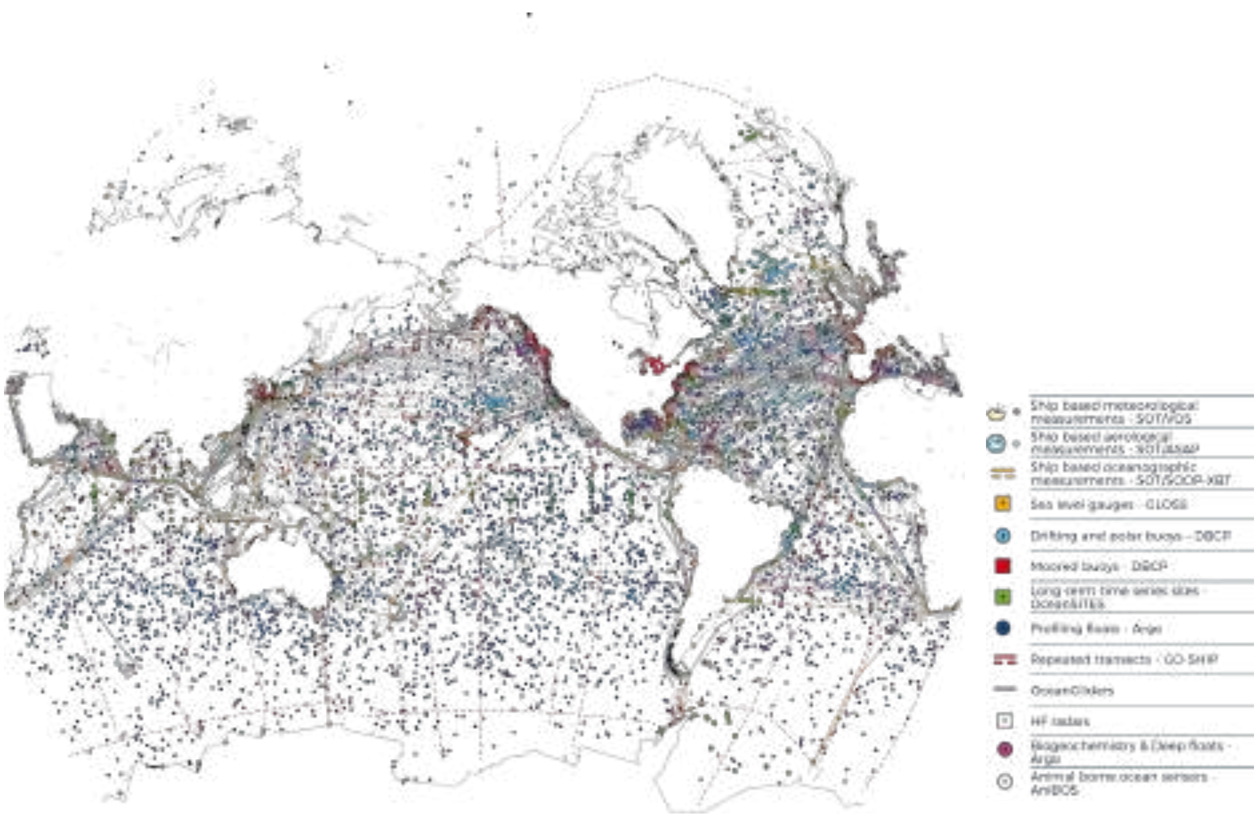

Figure 7.1. *In situ* Global Ocean Observing System.
Note: Dashed lines for GO-SHIP and SOOP have not been sampled after the impact of Covid-19; dots for VOS and ASAP show May 2021 observations. This image is not to scale – dots are shown at a size of 100 km for visibility. *Source*: OceanOPS in June 2021: operational platforms latest location (Argo, DBCP, AniBOS, VOS, ASAP); fixed platforms location (GLOSS, HF radars, OceanSITES); reference lines (GO-SHIP, SOOP); sampled sites (OceanGliders).

through an expanded use of autonomous instruments and new technologies, such as drones (Foltz et al., 2022). However, resources remain constrained to address these needs. Moreover, research funding, which supports a large portion of the current system, is often not assured beyond the short lifetime (3–5 years) of a research project.

Transformational initiatives to expand and strengthen the GOOS are endorsed as actions under the Ocean Decade and in the GOOS 2030 Strategy implementation (Fischer et al., 2019). These represent clear pathways to meet societies' pressing need for the right ocean information, including carbon and marine biodiversity observations, extreme weather forecasting and observations in coastal areas, and countries' Exclusive Economic Zones, as well as the deep ocean. These initiatives will improve data infrastructure and coordination within the GOOS, co-design its development to make it fit for purpose, and expand it by increasing opportunities for collaboration.

Implementing a truly integrated GOOS that delivers essential services to society will demand a step change in the level and effectiveness of partnerships across the scientific, end-user communities and the private sector – including philanthropists and citizens. GOOS has embraced this challenge, with programmes, projects and actions underway in all the areas highlighted above, and welcome dialogues about how to support this fit-for-purpose expansion of the ocean observing system.

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Challenge 8.
Create a digital representation of the ocean

Through multi-stakeholder collaboration, develop a comprehensive digital representation of the ocean, including a dynamic ocean map, which provides free and open access for exploring, discovering and visualizing past, current and future ocean conditions in a manner relevant to diverse stakeholders.

Implementation of FAIR data practices for the Global Ocean Observing System' *in situ* components

Emma Heslop, Mathieu Belbeoch, Ward Appeltans, Kevin O´Brien and Pieter Provoost

It is essential for a Global Ocean Observing System (GOOS) to develop and invest in an efficient data infrastructure that meets the requirements of a growing range of users, in accordance with the FAIR data principles (Findability, Accessibility, Interoperability and Reusability). While these principles are largely accepted, their practical implementation needs further guidance, efforts and prioritization.

Most GOOS Observations Coordination Group (OCG) observing networks deliver data in real time, where applicable. However such real-time data are not always made available through global data nodes that are easily locatable and accessible for non-experts via harmonized formats and services enabling interoperability. Delayed-mode delivery of high quality data (key for climate analysis) requires human capacity for quality control and continuous monitoring of sensor performance. Non-standardized, or simply missing, quality controlled procedures have a high impact on the uncertainty of the data and limit their usability. Globally adopted quality control procedures are well established for physical essential ocean variables (EOVs), including machine learning methods, but still under development for biogeochemical EOVs.

Metadata are at the heart of the FAIR principles, and they are fundamental not only for users but also for system performance monitoring, coordination and centralized support. The quality of metadata[13] gathered and integrated by the WMO-IOC OceanOPS Center for each network is in progress but there is still room for improvement for some GOOS components facing obstacles such as lack of resources (e.g. data managers). The annual *GOOS Ocean Observing System Report Card*[14] reports on the performance of the data flow across real-time and delayed-mode data and metadata, from each of the 12 global observing networks coordinated under the OCG (Figure 8.1).

The Ocean Biodiversity Information System (OBIS) of the IOC acts as the global data platform for biological and ecosystem essential ocean variables (BioEco EOVs) under GOOS and the Group on Earth Observations Marine Biodiversity Observation Network (MBON) (Figure 8.2). OBIS has been running for 22 years now, and over the last year, despite COVID-19, has seen an exponential growth in the amount of data. OBIS integrates nearly 100 million records (+100,000 records per day), 4,418 datasets (+2 datasets per day). Some of this growth is due to the newly added capability for publishing DNA-derived data. One-third of the data in OBIS (about 37 million records) are from sampling events before 2000, with 5.5 million records from sampling events before 1970. These older data provide an important baseline that enables comparative analysis over time. There is often a delay of 5 to 10 years in publishing biological data in the public domain, resulting in fewer records for more recent years.

13 https://www.ocean-ops.org/metadata

14 https://www.ocean-ops.org/reportcard2021/

GOOS *in situ* networks [1]	Implementation: Status [2]	Data & metadata: Real time [3]	Data & metadata: Archived delayed mode [4]	Data & metadata: Meta-data [5]	Best practices [6]	GOOS delivery areas [7]: Opera-tional services	GOOS delivery areas [7]: Climate	GOOS delivery areas [7]: Ocean health
Ship based meteorological measurements - SOT/VOS	★★☆	★★★	★★★	★★☆	★★☆	✓	✓	
Ship based aerological measurements - SOT/ASAP	★☆☆	★★★	☆☆☆	★★☆	★☆☆	✓	✓	
Ship based oceanographic measurements - SOT/SOOP-XBT	★★☆	★★★	★★★	★★☆	★★☆	✓	✓	
Sea level gauges - GLOSS	★★★	★★☆	★★★	★☆☆	★★☆	✓	✓	
Drifting and polar buoys - DBCP	★★★	★★★	★★☆	★★☆	★★☆	✓	✓	
Moored buoys - DBCP	★★☆	★★★	★★☆	★★☆	★★☆	✓	✓ O_2	
Long-term time series sites - OceanSITES	★★☆	Not applicable	★★☆	★★☆	★★☆		✓ O_2	✓ O_2
Profiling floats - Argo	★★★	★★★	★★★	★★★	★★☆	✓	✓	
Repeated transects - GO-SHIP	★★★	★☆☆	★★★	★★☆	★★★		✓ O_2	✓ O_2
OceanGliders	★☆☆ Emerging	★★☆	★☆☆	★★★	★☆☆	✓	✓ O_2	✓ O_2
HF radars	☆☆☆ Emerging	★★★	★★★	★☆☆	★★★	✓	✓	
Biogeochemistry & Deep floats - Argo	★☆☆ Emerging	★★★	★☆☆	★★★	★★☆		✓ O_2	✓ O_2
Animal borne ocean sensors - AniBOS	☆☆☆ Emerging	★★★	★★☆	★☆☆	★★☆	✓	✓	✓

(1) More information at goosocean.org (2) Status: status vs target, external target when exists, *e.g.* GCOS; network self-assessed status when target does not exist (3) Real time: data available on Global Telecommunication System of WMO or another global internet based data node (GDAC) with a proper quality control mechanism; OceanSITES metocean real-time data is managed by DBCP (4) Archived high quality: self-assessed status on the availability of delayed mode data, on the web, including all historical data (5) Metadata: information required by OceanOPS (6) Best Practices: community reviewed and easily accessible documentation encompassing the observations lifecycle (7) See Network Specification Sheets: goosocean.org > Observations > Network Specification Sheets

Figure 8.1. Status table for the 12 global ocean observing networks coordinated by OCG. Supported through OceanOPS monitoring. *Source:* GOOS Ocean Observing System Report Card 2021, https://www.ocean-ops.org/reportcard2021/.

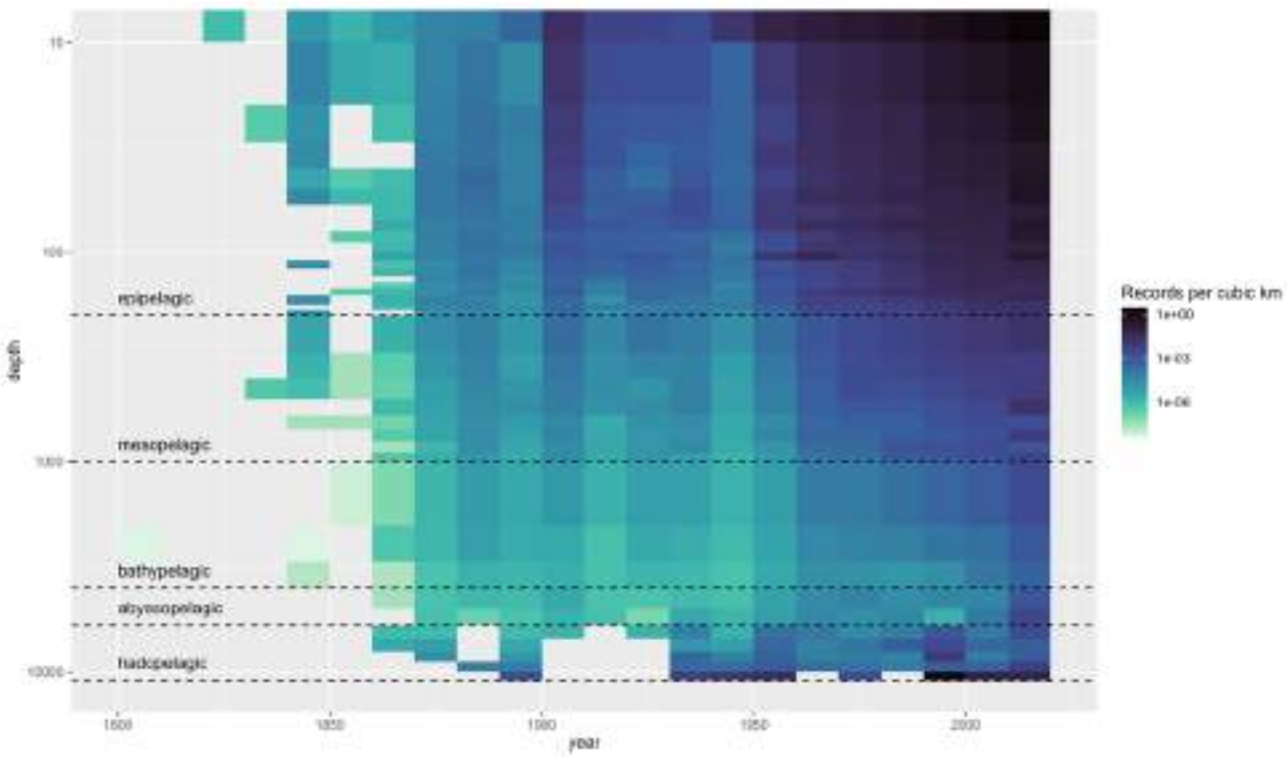

Figure 8.2. The number of records in OBIS per volume (km^3) by depth and by year (produced on 23 Feb 2022). *Source:* OBIS.

Free and unrestricted data access, encouraged recently by the new WMO Unified Data Policy, remains a commonly agreed rule across all GOOS networks, although some policies and data infrastructure are still under development. Many of the challenges are logistical, legal (in waters under national jurisdiction) or technical; however the need for data management is not always sufficiently prioritized in a system predominantly supported through research-oriented projects.

A recent survey published by Satterthwaite et al. (2021) showed that of around 300 active long-term biological observing programmes, only half store their data in a long-term data repository and only a quarter provide public access to their data. However, of those that did not provide public access, 75% reported that they would be willing to publish data to OBIS if they had the required resources and know-how.

The OCG has undertaken a data and metadata mapping to better monitor the complexity of the existing global data flows for the 12 OCG ocean observing networks, and to identify the strengths and weaknesses of the data system from observations to interoperable and harvestable data nodes. This will support the development of practical recommendations for an OCG Data Implementation Strategy (to be released mid-2022) and to help observing networks gain support for the implementation of FAIR data practices. When it comes to integrating the diversity of observing systems at the coast and unlocking the potential of new networks and systems, resourcing international coordination initiatives – such as the OCG, OceanOPS and OBIS – aids the integration of new flows with existing international and national infrastructure, supporting cost efficiency and FAIR data delivery. Emerging networks, such as autonomous underwater vehicles (OceanGliders), animal-borne ocean sensors (AniBOS) and high-frequency radars (HF Radar) that have joined the OCG are already structuring their contribution and preparing a robust data flow inspired by the most successful networks.

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Ocean data sharing – A global and essential requirement in the value chain

Peter Pissierssens, Lucy Scott, Claudia Delgado and Ward Appeltans

Data and information of high and known quality are essential in the value chain between research, observation, data and information management, products and services, and decision-making. Digitizing, preserving, managing, exchanging and, most importantly, using a significantly increased volume and range of ocean-related data, information and knowledge will be cornerstones of the success of the UN Decade of Ocean Science for Sustainable Development and beyond.

Ocean data represents an economic opportunity as focus globally is shifting towards sustainable use of the ocean. Data sharing can be a catalyst for the establishment and growth of new and existing sustainable industries. It can be used to create metrics that guide decision-making for existing industries seeking to operate in a more sustainable way. Data sharing can also drive data-driven businesses that help non-experts to benefit from the wealth of data we are already producing about our oceans.

The International Oceanographic Data and Information Exchange (IODE) programme of the Intergovernmental Oceanographic Commission (IOC) of UNESCO was established in 1961. Its purpose is to enhance marine research, exploitation and development by facilitating the exchange of oceanographic data and information between participating Member States, and by meeting the needs of users for data and information products. The IODE programme developed a network of data centres around the globe, hosted and operated by IOC Member States. The mission of a National Oceanographic Data Centre (NODC) is to provide access and stewardship for the national resource of oceanographic data. This effort requires the gathering, quality control, processing, summarization, dissemination and preservation of data generated by national and international agencies. In addition, the IODE Associate Data Unit (ADU) is intended to bring in the wider ocean research and observation communities as key stakeholders of the IODE network, taking into account the growth of ocean research and observation programmes and projects, and the ability of these projects to establish data systems. It is important for these communities to share, provide access to and preserve all ocean research and observation data.

Today, the IODE network includes 93 data centres (60 NODCs and 33 ADUs, of which 18 are in Africa, 10 are in Latin America and 9 are in the WESTPAC region) in 68 countries (Figure 8.3). Most of these data centres provide data services online and also contribute data to the World Ocean Database (WOD), the world's largest collection of vertical profile data of ocean characteristics available internationally without restriction; and the Ocean Biodiversity Information System (OBIS), a global open-access data and information clearing house on marine biodiversity for science, conservation and sustainable development.

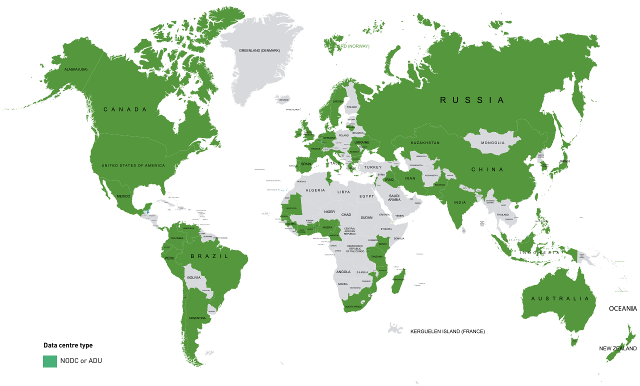

Figure 8.3. Global map of IODE data centres. *Source*: IODE, April 2022.

A major challenge for most users of the data (especially those held by the national data centres) is the sheer number of online data sources. The IOC, through its IODE programme, therefore decided to develop the Ocean Data and Information Service (ODIS), an e-environment where users can discover data, data products, data services, information, information products and services provided by Member States, projects and other partners associated with the IOC. ODIS will interlink distributed, independent, systems (within and outside of the IOC) through a decentralized interoperability architecture (ODIS-Arch) to form a digital ecosystem. As with natural ecosystems, ODIS will be resilient to the gain or loss of parts, and accommodate a wide diversity of products and services, while maintaining its core functions.

The IOC's Ocean InfoHub Project (OIH) has facilitated the development of the first phase of the ODIS architecture through engaging the IOC and global partners, as well as partners and end users in three communities of practice: Africa; the Latin America and Caribbean region; and the Pacific Small Island Developing States. The project is supporting the implementation of the ODIS architecture in distributed resources including existing clearing house mechanisms. The OIH is not only designed to be an access point for ocean data and information for users, but also as a mechanism to allow scientists and other data and information providers to share their content globally, while still retaining ownership.

Another element needed to ensure equitable global sharing of data and information is free and open access, and for this reason the IOC adopted the IOC Data Policy in 2003, which is now being updated to take into consideration the new requirements of the UN Decade of Ocean Science for Sustainable Development.

Additional resources

- IODE **https://iode.org**
- OBIS **https://obis.org**
- ODIS **https://oceaninfohub.org/odis/**
- Ocean Infohub **https://oceaninfohub.org**
- WOD **http://wod.iode.org**

The challenge to map the global seafloor – Providing data to help us understand our ocean

Marzia Rovere, Aileen Bohan, Caroline Bringensparr, Evert Flier, Jamie McMichael-Phillips, Helen Snaith, Pegah Souri and Pauline Weatherall

Knowing the shape and depth of the seafloor (bathymetry) is fundamental to understanding interactions between ocean circulation, climate change and weather forecasting; tides and wave action; sediment transport; tsunami wave propagation; and underwater geohazards, as well as geological processes and biological systems. Seabed mapping is also vital for the security, safety and economic wealth of nation states as it underpins the estimation of natural resources, such as seabed minerals and fishing grounds. Yet, the majority of the ocean depths remain unmapped and unmeasured by modern echo-sounding techniques and are mostly inferred from satellite altimetry data with very coarse km-scale resolutions that return only a crude representation of the shape of the ocean seafloor (Figure 8.4).

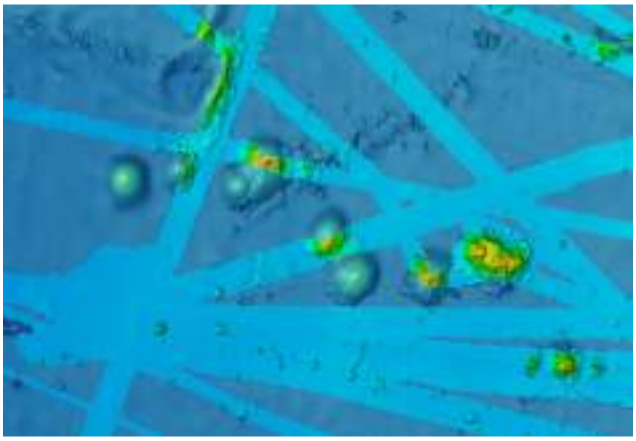

Figure 8.4. Tracklines of bathymetry measured by modern sonar systems superimposed over satellite-derived representation of a portion of the Pacific Ocean seafloor. Seamounts that appear as bulges in satellite-derived data are revealed in their morphological complexity by higher resolution multibeam echosounder data. Smaller-scale features, which are undetected in satellite data, appear in actual soundings that more accurately measure the depths of the ocean. *Source*: GEBCO/Seabed2030.

The General Bathymetric Chart of the Oceans (GEBCO) has been producing bathymetric data sets and charts since 1903. It operates under the joint auspices of the International Hydrographic Organization (IHO) and Intergovernmental Oceanographic Commission (IOC) of UNESCO. In 2017, The Nippon Foundation of Japan partnered with GEBCO to set up the Nippon Foundation-GEBCO Seabed 2030 Project (Seabed 2030) with the goal of mapping 100% of the world ocean floor by 2030.

This requires an international effort to identify and consolidate existing bathymetric data within national and international data repositories, the hydrographic and scientific communities, and industry. Areas of sparse data coverage also need to be identified to help plan future data collection initiatives.

An important activity of the Seabed 2030 Project has been to identify how much of the seafloor has been mapped, and to monitor progress towards 100% coverage. Figure 8.5 shows the percentage increase from 6.7% in 2014 to 20.6% of the data sets made available from different stakeholders and included in the GEBCO grids from 2019 (when the project took over the production of the global charts) through to 2021. Figure 8.6 shows the GEBCO_2021 Grid. This map does not represent all globally existing data, because many are still under embargo within the private sector and Member States of IOC and IHO. GEBCO and Seabed 2030 are working hard to identify, assimilate and make them available for the benefit of all.

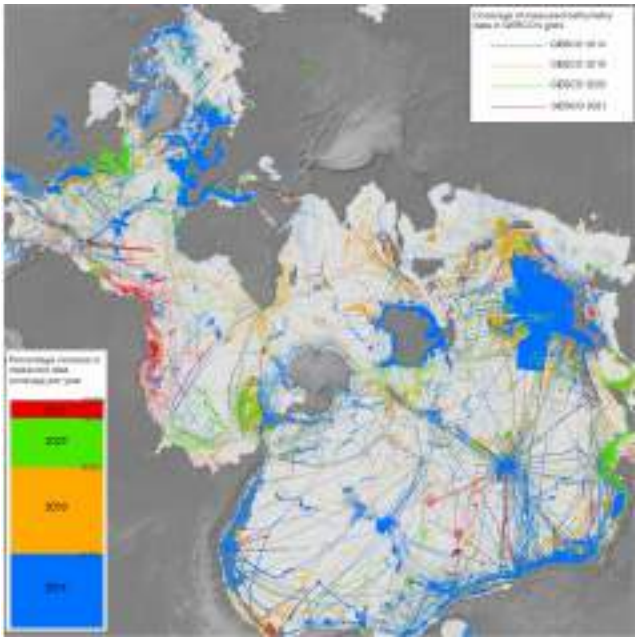

Figure 8.5. Spilhaus projection showing percentage increase in the coverage of the seafloor mapped in GEBCO's gridded data sets from 2014 (the last GEBCO release before Seabed 2030) to 2021. The percentage is based on a set of spatial resolutions in the range 100–800m depending on the depths of the seafloor. For example, in the depth interval 0–1,500 m, a spatial resolution of 100m is feasible to achieve the goal of mapping 100% of the world ocean floor by 2030 (see Mayer et al., 2018). *Source*: GEBCO/Seabed2030.

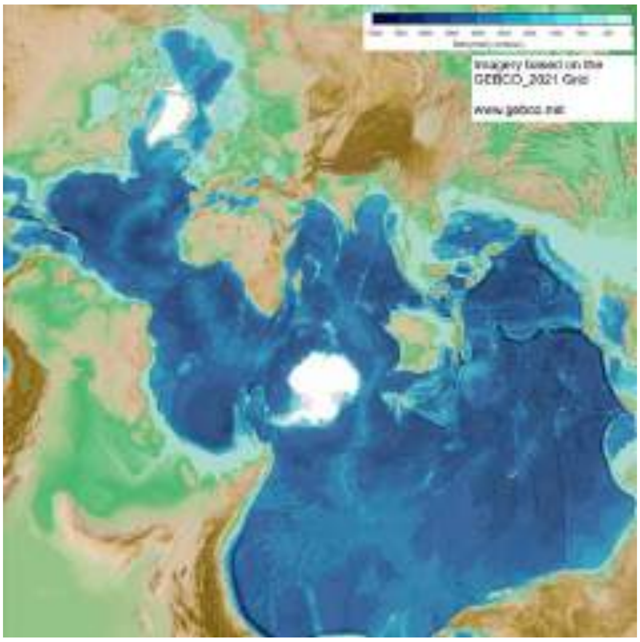

Figure 8.6. GEBCO_2021 grid in Spilhaus projection showing that all oceans and sea basins are connected into one ocean. The mid-ocean ridges of the Atlantic, Indian and Pacific Ocean are particularly evident. *Source*: https://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_2021/.

To achieve this goal, Seabed 2030 builds partnerships and raises awareness of the need to map the global seafloor. To date, the project has benefitted from a number of data collection initiatives, including new technologies, such as autonomous uncrewed surface vehicles (USVs), which help collect new data in previously unchartered waters. Private entities and citizens can participate in increasing our knowledge of the ocean by sharing depth measurements from their navigation instruments while at sea. These initiatives – collectively known as crowdsourced bathymetry – are now gaining momentum and help fill data gaps. Finally, improved availability and resolution of satellite optical sensors further contributes to the knowledge of coastal shallow waters.

Seabed 2030 therefore remains committed to working with the international data collection and mapping communities towards the goal of a complete map of the ocean seafloor.

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Additional resources

- GEBCO **https://www.gebco.net/**
- Seabed 2030 Project **https://seabed2030.org/**

Challenge 9. Skills, knowledge and technology for all

Ensure comprehensive capacity development and equitable access to data, information, knowledge and technology across all aspects of ocean science and for all stakeholders.

Delivering capacity development for the ocean we need for the future we want

Cláudia Delgado, Johanna Diwa, Peter Pissierssens and Greg Reed

The United Nations defines capacity development as a process of change. It is often equated with additional staff, training and workshops. While individual training and workshops may be part of a comprehensive capacity-development plan, they are not sufficient by themselves. For example, training an individual does not ensure that this training is then implemented in the workplace. Capacity development must be broader to address improvements in systems to improve performance and ensure sustainability.

The *IOC Criteria and Guidelines on the Transfer of Marine Technology* (IOC-UNESCO, 2005), recognized as a key component of CD in ocean science and observations by the UN Law of the Sea and consultations around BBNJ, provides the criteria and guidelines to promote capacity development in ocean- and coastal-related matters through international cooperation. The IOC Capacity Development Strategy focuses on six main outputs: 1) human resources developed, 2) access to physical infrastructure established or improved, 3) global, regional and subregional mechanisms strengthened, 4) development of ocean research policies in support of sustainable development objectives promoted, 5) visibility and awareness increased, and 6) sustained (long-term) resource mobilization reinforced.

One important element of capacity development is human resources development through continuous professional development initiatives, addressing output 1. For over a decade, the IOC (under the IODE programme) has developed the OceanTeacher Global Academy (OTGA). Its primary goals are to develop a portfolio of packaged courses (related to the needs of IOC and other partners and stakeholders) and to deliver courses through online and/or blended learning, on demand.

An unprecedented disruption at the global scale marked 2020 and 2021 but OTGA continued to quickly adapt and move to fully online training, having organized over 40 online training courses in 2020–2021 (Figure 9.1). In 2021, OTGA was able to move from the emergency remote learning done during the first year of the pandemic, to fully online learning, which resulted in a record number of participants benefiting from OTGA courses. Although English is the main language used in OTGA and OTGA-supported courses, other languages are used regularly to increase participation and uptake of the information for ocean action. In October 2021, OTGA became an endorsed Ocean Decade Project, contributing to many of its high-level objectives, challenges and outcomes. Complementary, OTGA works in partnership with the IOC Member States and its institutions, and now has a network of 17 Regional and Specialized Training Centres. Furthermore, the IOC Sub-Commission of the Western Pacific (IOC/WESTPAC) has developed a Regional Network of Training and Research Centres on Marine Science in the Western Pacific, aiming to accelerate transformations in capacity development, improve and sustain required capacity for ocean sustainability in the region.

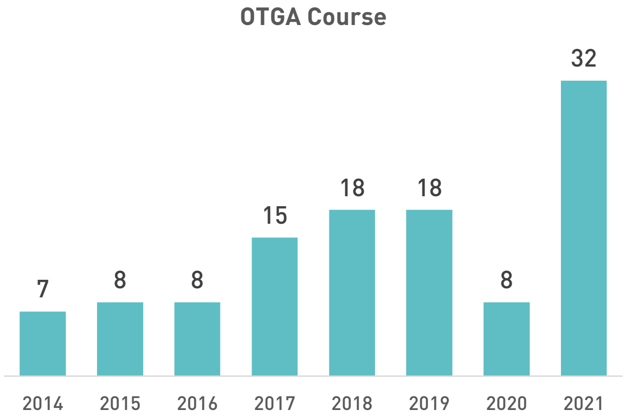

Figure 9.1. Number of courses organized and supported by OTGA (2014 –2021). *Source*: IOC-UNESCO

Further initiatives and activities addressing the other five outputs are:

- The development of the Ocean InfoHub, which facilitates access to global oceans information, data and knowledge products for management and sustainable development (output 2, 5).
- IOC capacity development surveys which identified regional specific capacity development needs used to develop capacity development projects and programmes of local and regional relevance (output 3, 4).
- An IOC consultation to collate information on ongoing and planned capacity development efforts to increase awareness, promote cooperation and reduce inefficiencies and duplication (output 5).
- A revised IOC capacity development strategy to align: related IOC activities with current needs

References

IOC-UNESCO. 2005. IOC Criteria and Guidelines on the *Transfer of Marine Technology* (CGTMT). Paris, UNESCO. (IOC Information Document 1203). doi:10.25607/OBP-405

Additional resources

- International Oceanographic Data and Information Exchange Programme of IOC-UNESCO **https://iode.org**

Human and financial capacity to support ocean science

Kirsten Isensee

The Global Ocean Science Report (GOSR) mechanism offers a global record of how, where and by whom ocean science is conducted (IOC-UNESCO, 2020). Based on data provided by IOC Member States and additional data collected independently by the IOC Secretariat, and through specialized consultants and agencies, under the supervision of the GOSR Editorial Board, it is now possible to obtain regular global, standardized information about the ocean science workforce, infrastructures, equipment, funding, investments, publications, data flow and exchange policies, as well as national strategies addressing ocean science for sustainable development. Ideally, key GOSR indicators should be collected more regularly to provide key trends during the UN Ocean Decade.

The number of ocean science researchers varies widely across countries

While new technologies are revolutionizing ocean science, human workforce considerations remain a constant for successful scientific programmes. The human component has to keep pace and will remain a continuously developing constant for the advancement of advance ocean science and science management, as well as science-to-innovation linkages, and the science-to-policy value chain. The number of ocean science researchers varies widely across countries – between <1 to >300 employees per million inhabitants. European countries tend to have the highest ratio of researchers as a proportion of the total population. For example, Norway and Portugal have more than 300 employed researchers per million inhabitants (Figure 9.2). However, if measured in relation to the gross domestic product (GDP), the numbers of ocean researchers in some developing countries (e.g. Benin, Guinea, Mauritania and South Africa) are comparable to or even higher than the numbers in some developed European countries like Belgium, Denmark, Ireland and Sweden.

Figure 9.2. Number of national ocean science researchers employed per million inhabitants. (HC = headcount; FTE = full-time equivalent, for the Islamic Republic of Iran and Colombia). *Source*: IOC-UNESCO, 2020.

Gender equality remains a challenge in ocean science

The latest information available at the global level shows that women account for some 7% (Democratic Republic of the Congo) to 72% (Ireland) of all ocean science personnel, including researchers and technical support staff. The global average stands at 37%. Still, ocean science does better than science in general, since female researchers account for 39% of global ocean scientists as compared to 33% of all researchers worldwide (UNESCO, 2021). Note that the proportion of female scientists varies greatly across countries, with values ranging from 12% (Japan) to more than 63% (Croatia). In Angola, Brazil, Bulgaria, Croatia, Dominican Republic, El Salvador, Mauritius, Poland and Suriname, 50% or more of ocean science researchers are women (Figure 9.3).

Some countries are 'punching above their weight' in the field of ocean science

The variation in human capacity is mirrored by differences in countries' investment in ocean research. Overall, the percentage of gross domestic expenditure on research and development (GERD) devoted to ocean science is noticeably smaller than that spent on other major fields of research and innovation, which was 1.8% of GDP (UNESCO, 2021). On average, only 1.7% of national research budgets are allocated for ocean science, with percentages ranging from 0.03% to 11.8% (Figure 9.4). Some countries are 'punching above their weight' in the field of ocean science, as they allocate a large proportion of their GERD to ocean science, despite having very low overall GERD, e.g. Peru and South Africa. However, reduction in ocean science budgets, as reported by nine countries over the time period 2013–2017, puts maintenance and improvement of technical and human capacity in ocean science at risk. In a different trend, based on the GOSR2020, 14 countries significantly increased their average budgets between 2013 and 2017.

Nevertheless, in order to fill existing knowledge gaps and deliver the science required for a sustainable ocean, ocean science funding and investment in its technical and human resources need to become priorities. Tracking better human and financial support for ocean science, based on comparable international indicators, will be indispensable. This evidence will contribute to the development of innovative and transformative ways of directing new investments and engaging new partners in ocean science for sustainable development.

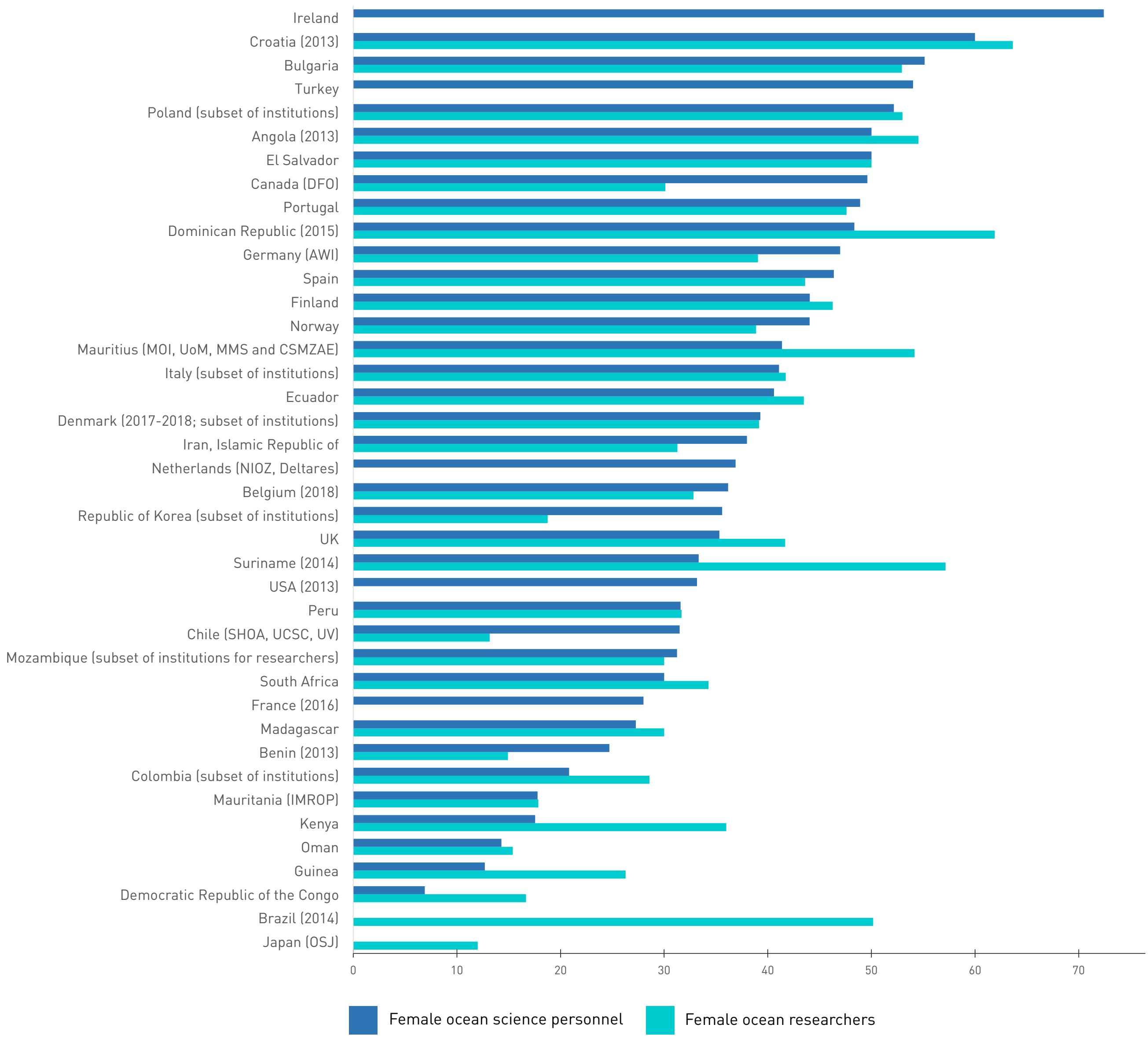

Figure 9.3. Proportion (% of total HC) of female ocean science personnel and female ocean researchers in 2017. In the absence of data for 2017, the latest available year is shown in brackets. *Sources:* Data based on the GOSR2017 and GOSR2020 questionnaires (researchers) and World Bank DataBank (inhabitants); IOC-UNESCO, 2020.

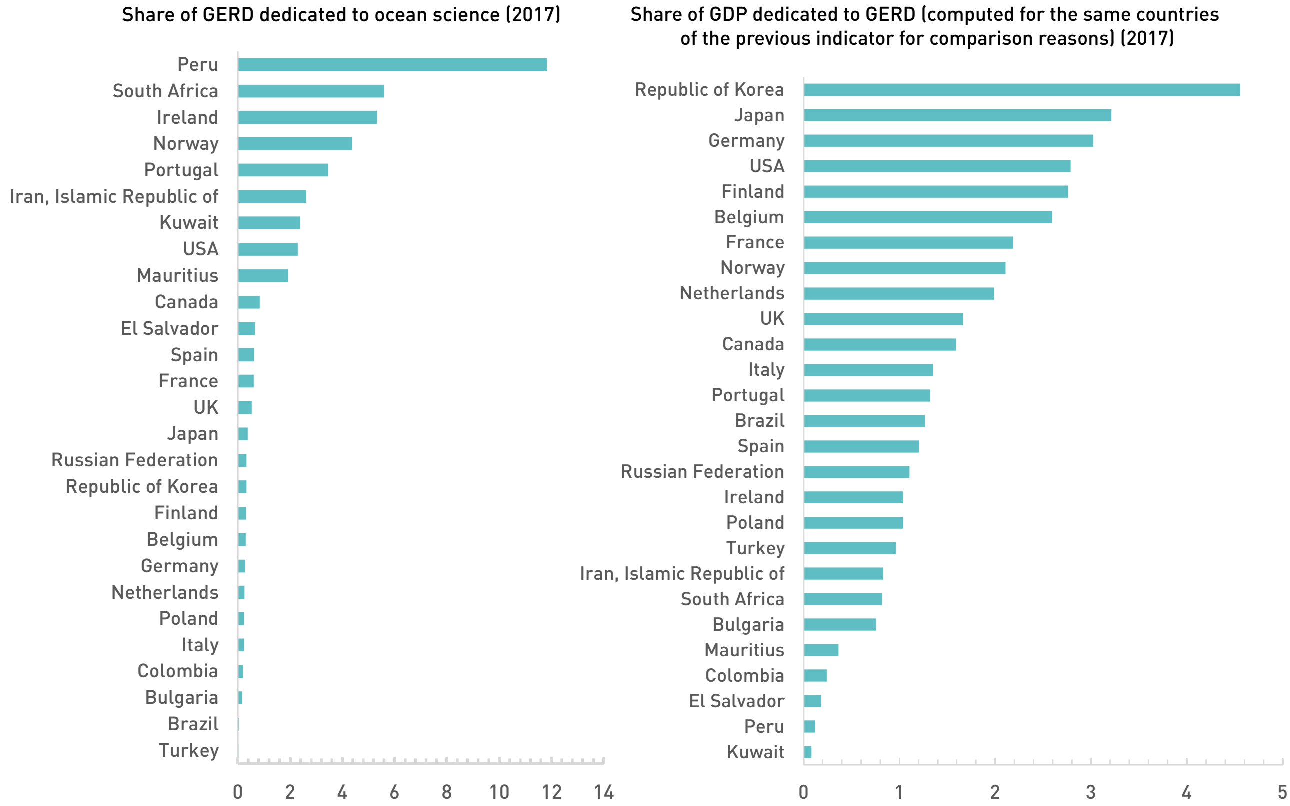

Figure 9.4. Estimates of ocean science funding as a share of GERD and GERD as a share of GDP in 2017. *Sources:* IOC-UNESCO, 2020; Data adapted from the GOSR2020 questionnaire and UNESCO Institute for Statistics database. Note that ocean science funding is not identified as such in GERD data and can be found in natural sciences and other categories.

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Additional resources

- GOSR portal **https://gosr.ioc-unesco.org/home**

Ocean best practices – supporting ocean observations and monitoring, underpinned by a global resource for discovering, equitably sharing and collectively advancing our methodological heritage

Cristian Muñoz , Jay Pearlman, Frank Muller-Karger and Johannes Karstensen

The ocean covers 70% of the Earth's surface and is an important resource for food, global transport, energy, global biodiversity and climate stability. Efficient monitoring and predicting of the ocean's condition are important for all of us. This requires a collaborative effort of global, national and local dimensions. To ensure that we can compare observations and detect changes from one place to another or over time, collaborative ocean observing should use well-defined and reproducible methods. Here, we call such methods 'Ocean best practices' (OBPs).

Significant challenges remain in implementing OBPs across groups observing the ocean: (i) methods are often not documented; (ii) there is no widely-adopted endorsement process to help point to which practice is best; and (iii) there are limited ways to find and access methods, even when they are documented. To help address these challenges, we need to promote consistent documentation and convergence of methodologies and make these documents available through an open 'library'.

The endorsed 'Ocean Practices for the Decade' Programme of the UN Ocean Decade ('OceanPractices') is addressing these challenges. Following known methods builds knowledge and trust about the information created for managing the oceans. Agreed methods, when they are widely adopted, support better interoperability between observations and data. Interoperability is a key aspect at this stage in the globalization of ocean knowledge to

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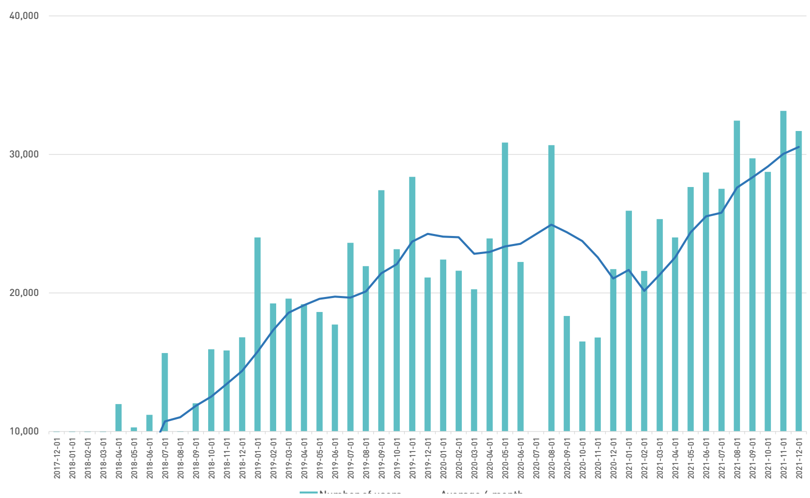

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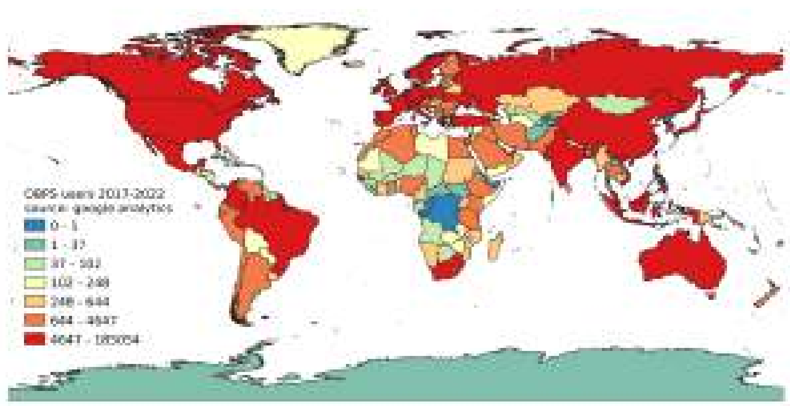

Figure 9.5. a) OBPS user access has grown three-fold in the last four years, **b)** number of users by country 2017-2022. *Source:* Google Analytics.

meet the objectives of the Ocean Decade. Scientists then understand better what has been done and how their own work relates to it. Many of the endorsed Ocean Decade programmes recognize the benefits and impacts of creating and using OBPs.

The OceanPractices programme is built upon the Ocean Best Practices System (OBPS), established in 2017. OBPS is a reference library of methods as well as a training resource. OBPS engages in collaborations and support of Ocean Decade actions through the OceanPractices Programme. Metrics from the OBPS are available to quantify user interest in best practices. Figures 9.5a and 9.5b. show the increase of document downloads over time; this reflects the growing interest in best practices on a global scale – users from all over the world have accessed the repository. A characteristic of the repository is its broad extent, covering science research and applications (Figure 9.6). A similar trend is emerging in the companion peer-reviewed journal *Frontiers of Marine Science* (Ocean Observing topic), which has had almost 250,000 views and contributions from 532 authors to date.

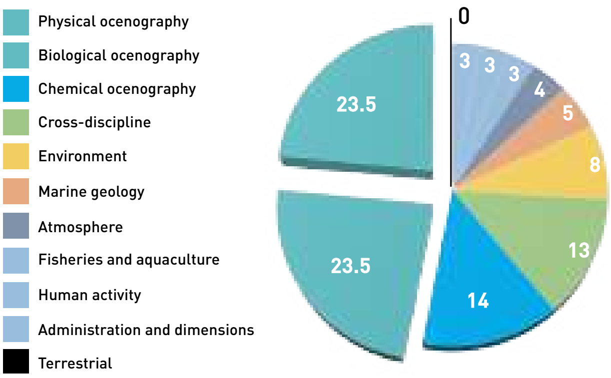

Figure 9.6. A range of methods in the repository covers the traditional physical, chemistry and biological sciences, as well as cross-disciplinary relevant techniques of observation and application. *Source:* OBPS, April 2022.

The UN Ocean Decade OceanPractices Programme is contributing to the adoption of best practices and helps ocean observers and resource managers to set priorities for accurate and timely information. OceanPractices is working to launch activities in underrepresented regions by mobilizing and promoting work on documentation for essential ocean variables (EOVs) and promoting collaborations to synthesize knowledge.

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Additional resources

- OBPS website: **https://www.oceanbestpractices.org/**
- Frontiers in Marine Science BPs in Ocean Observing Topic: **https://www.frontiersin.org/research-topics/7173/best-practices-in-ocean-observing**

Challenge 10.
Change humanity's relationship with the ocean

Ensure that the multiple values and services of the ocean for human wellbeing, culture, and sustainable development are widely understood, and identify and overcome barriers to behaviour change required for a step change in humanity's relationship with the ocean.

Advancing ocean literacy research and practice is crucial for future ocean sustainability

Emma McKinley and Ronaldo Christofoletti

Enhancing global ocean literacy is critical to the future sustainability of the ocean, coasts and seas. Recent years have witnessed a growing emphasis on the need to understand the complex relationships between society and the ocean. The UN Decade of Ocean Science for Sustainable Development (2021–2030) (hereafter UN Ocean Decade) calls for a transformation in these relationships and has positioned the concept of ocean literacy as the key mechanism for change. Originating in the USA in the early 2000s and grounded in seven key principles (Table 10.1), the most common definition of ocean literacy is having 'an understanding of our influence on the ocean and its influence on us' (Santoro et al., 2017). Initially framed around knowledge and formal education, ocean literacy has evolved, moving away from a knowledge focus to one which accounts for the complexity of relationships between society and the ocean, including knowledge, awareness, attitudes, communication, activism and behaviour (Brennan et al., 2019) and, more recently, emotions, access and experience, trust and transparency, and adaptive capacity (McKinley and Burdon, 2020).

Table 10.1. The seven principles of ocean literacy

Ocean Literacy Principle #1	The Earth has one big ocean with many features.
Ocean Literacy Principle #2	The ocean and life in the ocean shape the features of Earth
Ocean Literacy Principle #3	The ocean is a major influence on weather and climate
Ocean Literacy Principle #4	The ocean made the Earth habitable
Ocean Literacy Principle #5	The ocean supports a great diversity of life and ecosystems.
Ocean Literacy Principle #6	The ocean and humans are inextricably interconnected.
Ocean Literacy Principle #7	The ocean is largely unexplored.

Source: IOC-UNESCO, 2021*a*.

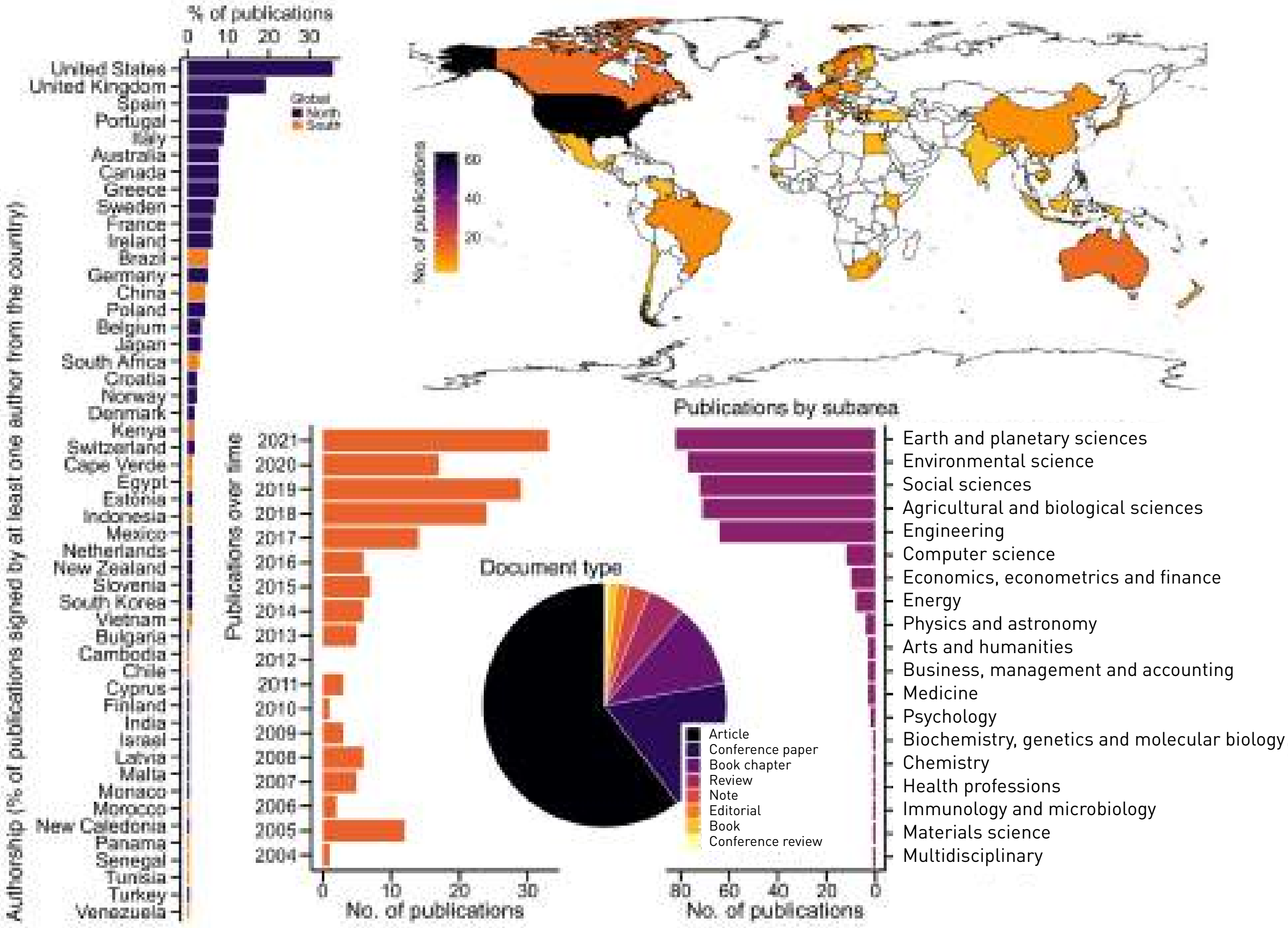

Figure 10.1. Publications in ocean literacy in *Scopus*, including terms 'ocean literacy' or 'ocean literate' or 'coastal literacy'; accessed on 15 March 2022. Results are presented by contribution per country, distinguished by Global North and South, considered by the number of papers in which a given country has at least one author; by distribution over time, area of knowledge and document type. *Source*: www.scopus.com

The growth in interest in ocean literacy has been mirrored by a growing global community of researchers and practitioners. Ocean literacy research has been gathering increasing attention since the announcement of the UN Ocean Decade in 2017, reaching 181 publications in *Scopus*, of which 61% have been published since 2018 (Figure 10.1). Also, since the launch of UN Ocean Decade in 2021, >64,500 individuals have accessed the IOC-UNESCO Ocean Literacy Portal (March 2021 to February 2022) and >600 participants from different age groups, with the majority identifying as female, attended IOC-UNESCO's ocean literacy training courses (Figure 10.2). Participants in these courses represent the diversity and transformation aspirations of the UN Ocean Decade related to gender and age, although the contributions by economic reality are still uneven. While there is a balance of Global North and South with 50:50 participants in capacity-building opportunities (Figure10. 1), a minority of ocean literacy publications were signed by Global South authors (Figure 10.2), reflecting the reality of production in other ocean science areas.

Looking to the future, global ocean literacy initiatives will benefit from investments in the ocean framework for action (IOC-UNESCO, 2020) strengthened through the Ocean Literacy With All programme (OLWA), launched in 2021, which will promote and monitor research, projects, capacity development, resources and networks (IOC-UNESCO, 2021*b)*. Numerous initiatives have been implemented globally, such as the EU4Ocean programme, the International Pacific Marine Educators Network (IPMEN) that links traditional knowledge with ocean literacy, and the International Ocean Literacy Survey which has been collecting data since 2015, focusing on ocean science understanding of 15–17-year-olds. Other notable work includes the development of the Canadian Ocean Literacy Strategy in 2020 (Canadian Ocean Literacy Coalition, 2021), the first national strategy of any country, and the UK's recent Ocean Literacy Survey (n=8244) which found 85% of respondents indicated that protecting the marine environment was important to them, and that while over 70% were willing to change behaviour, 36% felt their lifestyle had no impact on the marine environment (DEFRA, 2021). Such survey and strategy work, as

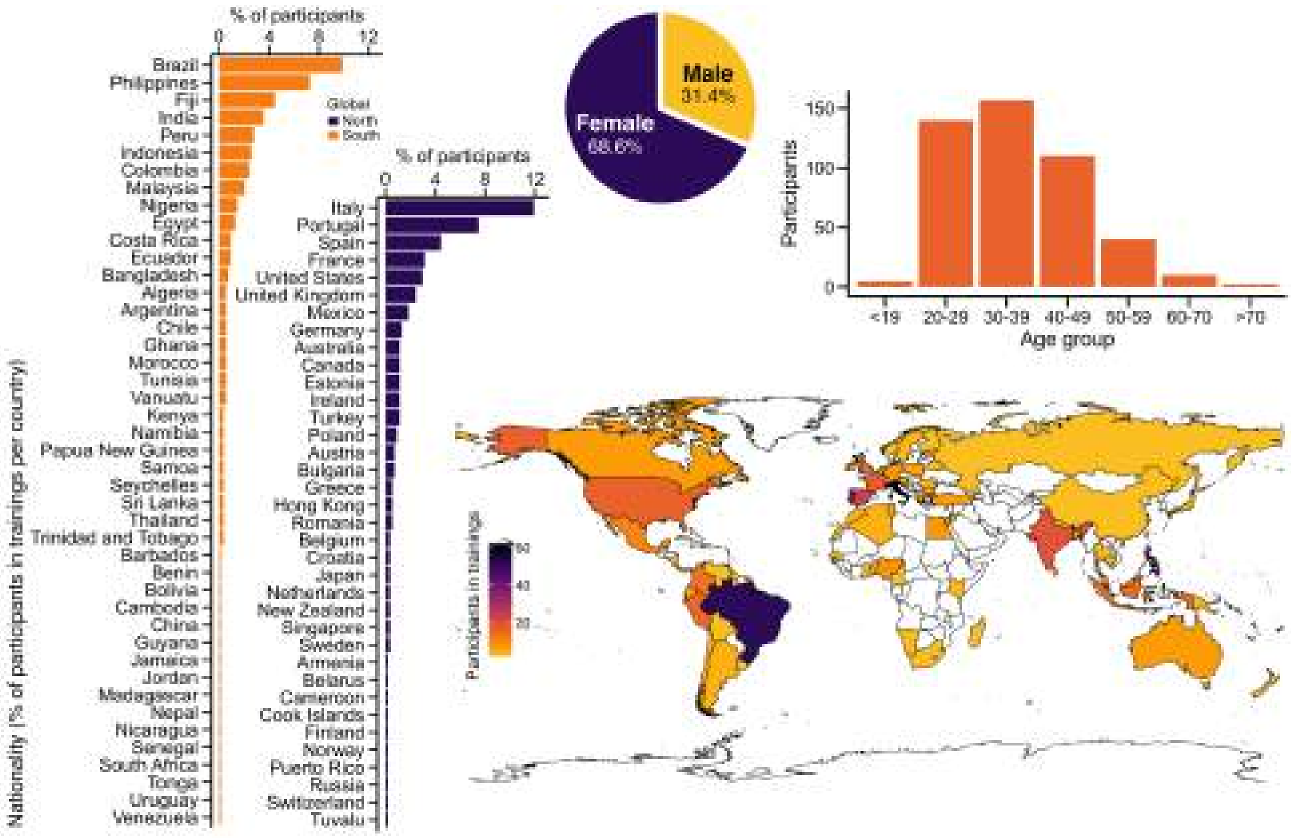

Figure 10.2. Participants in IOC-UNESCO's ocean literacy training courses for public, media, journalists, educators and governance sector. *Source:* IOC-UNESCO Ocean Literacy Portal, April 2022.

examples, provide much needed insight and highlight where efforts to enhance ocean literacy are required. In 2021, a further milestone for ocean literacy was achieved by the first Ocean Literacy Law, which mandates ocean literacy in the curriculum in Santos, Brazil (IOC-UNESCO, 2022). This supports other ocean literacy indicators in responding to the UN Ocean Decade Implementation Plan (IOC-UNESCO, 2021*a)*, achieving the three objectives: i) Identify required knowledge for sustainable development, ii) Generate comprehensive knowledge and understanding of the ocean and iii) Increase the use of ocean knowledge.

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Additional resources

- EU4Ocean programme **http://www.eu-oceanliteracy.eu**
- International Pacific Marine Educators Network **https://ipmen.net/**
- A Global Ocean Literacy Research Community (arcgis.com) **https://storymaps.arcgis.com/stories/6d44e8eb3cc84907a1e9f9ef56557cf1**
- UNESCO Ocean Literacy Portal **https://oceanliteracy.unesco.org/**

Ocean Decade

The science we need for the ocean we want

UN Decade of Ocean Science for Sustainable Development

Alison Clausen and Julian Barbiere

The United Nations Decade of Ocean Science for Sustainable Development – the Ocean Decade – was born out of a recognition that lack of ocean knowledge is hindering humanity's ability to manage the ocean sustainably and thus achieve global aspirations for climate, biodiversity and human well-being. Proclaimed in 2017 by the United Nations General Assembly, the Ocean Decade has the vision of the science we need for the ocean we want. It provides an inclusive, equitable and global framework for diverse actors to co-design and co-deliver transformative ocean science to meet ten Ocean Decade Challenges, which represent the most pressing and immediate needs for ocean science. These Challenges are used to structure Decade Actions to achieve collective impact (Table OD.1).

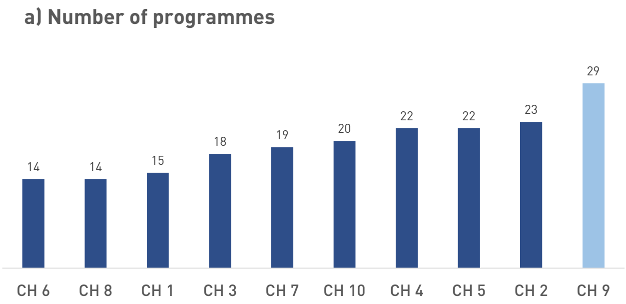
Calls for Decade Actions are the main mechanisms by which partners around the world are invited to have initiatives formally recognized as part of the collective Ocean Decade movement. The first Call for Decade Actions No. 01/2020 was open from 15 October 2020 to 15 January 2021 and was open to programme submissions of any broad thematic or geographic focus, as well as contributions of in-kind or financial resources. Over 230 submissions were received, collectively addressing all ten Ocean Decade Challenges and covering all major ocean basins (Figure OD.1). The results of the analyses led to the endorsement by the IOC Executive Secretary of 31 Decade programmes, 83 Decade projects and 42 Decade contributions. Ten UN-led Decade Actions were also registered through this process.[13] The remaining submissions were classified as pipeline Decade Actions that required further discussion and work before endorsement and this process is ongoing.

Table OD.1. Ocean Decade Challenges

Knowledge and solutions challenges	Infrastructure challenges	Foundational challenges
1. Understand and beat marine pollution	6. Increase community resilience to ocean hazards	9. Skills, knowledge and technology for all
2. Protect and restore ecosystems and biodiversity	7. Expand the Global Ocean Observing System	10. Change humanity's relationship with the ocean
3. Sustainably feed the global population	8. Create a digital representation of the ocean	
4. Develop a sustainable and equitable ocean economy		
5. Unlock ocean-based solutions to climate change		

Source: IOC-UNESCO.

15 A full list of endorsed Decade Actions can be found on http://oceandecade.org.



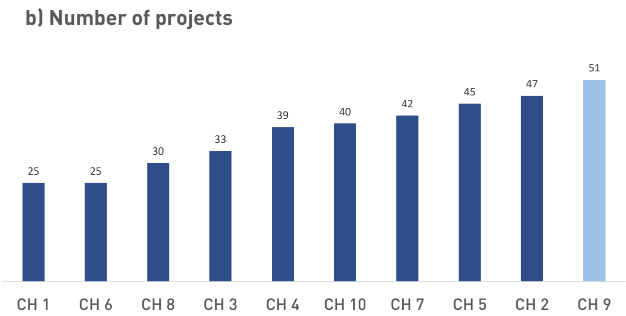


Figure OD.1. Number of endorsed Ocean Decade Actions (April 2022, first call for Decade Actions); **a)** endorsed Ocean Decade Programmes by Challenge; **b)** endorsed Ocean Decade Projects. *Source*: IOC-UNESCO.

Call for Decade Actions No. 02/2021 opened on 15 October 2021 and closed on 31 January 2022. This Call solicited Decade programmes that addressed Challenge 1: Marine pollution, Challenge 2: Multiple stressors on marine ecosystems and Challenge 3: Ocean-climate nexus, as well as projects to contribute to endorsed Decade programmes. This Call received 38 programme submissions and 134 project submissions (Figure OD.2).

Seven regional task forces have been established and are actively working to translate global priorities to the regional context. An Arctic Action Plan has been developed and an African Action Plan is nearing completion. Regional programmes have been endorsed for the Pacific SIDS and Mediterranean Sea, and one is in preparation for the Southern Ocean. The Tropical Americas and Caribbean Region is developing a series of Decade Actions based on the results of the Regional Kick-Off Conference held in December 2021. Other regional task forces have been engaged in the co-design and submission of Decade Actions.

To date, 26 National Decade Committees have been established and. and are acting as voluntary structures to convene stakeholders, coordinate Decade Actions, mobilize resources and increase outreach. There are few National Decade Committees to date in Least Developed Countries or Small Island Developing States (Table OD.2).

Social media is instrumental for the promotion of Decade Actions, stories, events, publications, etc., helping the Decade Coordination Unit dialogue and engage with different types of audiences about various causes. It is also a way to encourage closely related networks and partners to actively drive awareness about the Decade through their own channels. Social media outreach is a key means of measuring global engagement in the Decade. As of April 2022, the numbers of followers are: 5,896 Twitter, 2,048 Facebook, 4,063 LinkedIn and 2,924 Instagram.

In terms of resource mobilization, a review of the existing endorsed Programmes revealed that they have leveraged close to USD 844 million, representing approximately 24% of required costs. A funding gap of USD 2.7 billion has been identified based on this preliminary analysis, although USD 1.9 billion of this gap is attributable to a single Programme. As of April 2022, USD 15 million has been leveraged for co-sponsored Calls for Decade Actions with five partners. The Ocean Decade Alliance – a major element of the resource mobilization strategy – has 15 institutional members and 9 individual members (Patrons).

Table OD.2. Established National Decade Committees (April 2022).

National Decade Committees (as of April 2022)	
Angola	Republic of Korea
Brazil	Madagascar
Cabo Verde	Mexico
Canada	New Zealand
Chile	Nigeria
Colombia	Norway
Finland	Slovenia
France	Sweden
Germany	Russian Federation
India	Spain
Iran (Islamic Republic of)	Turkey
Italy	United Kingdom of Great Britain and Northern Ireland
Japan	United States of America

Source: IOC-UNESCO

Intergovernmental
Oceanographic
Commission

State of the Ocean Report 2022

Pilot edition

The current state of the ocean 2022

A renewed focus on the ocean and appreciation of its crucial role for life on Earth, the global climate, food security, human health and well-being, as well as the global economy, have led to increased demand by decision-makers and society at large for relevant, strategic, current and easily accessible information on the current state of our ocean.

This pilot State of the Ocean Report (StOR) aims to demonstrate the value of a periodic publication to inform stakeholders and the general public of key changes to the current ocean state.

The StOR is expected to become a seminal publication that will contribute significantly to mobilizing global society to act towards the 'ocean we need for the future we want'.

Subsequent full editions will invite UN agencies and professional organizations to contribute, turning StOR into a pan-UN publication. The full StOR will provide the basis for policy action, support decisions on research focus areas that need to be strengthened or developed and assist in the implementation of stronger science-based governance frameworks at national and global levels by strengthening the science-policy interface.

For further information, visit the IOC-UNESCO website at https://ioc.unesco.org.

One planet
One ocean
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