STATE OF THE OCEAN REPORT

2024

unesco
Intergovernmental
Oceanographic
Commission

2021 2030 United Nations Decade
of Ocean Science
for Sustainable Development

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2021 United Nations Decade
2030 of Ocean Science
for Sustainable Development

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Foreword

Vidar Helgesen
Executive Secretary of the Intergovernmental Ocenographic Commission of UNESCO

Considering just how much the ocean means to people and planet, the world ought to be kept up to date about its state. The fact is: we don't know (enough).

When the first State of the Ocean Report (StOR) was launched in 2022, we learnt that the quantitative description of the ocean is drastically incomplete and, as a result, current knowledge is insufficient to effectively inform solutions to the multiple ocean crises that humanity is now facing.

In this State of the Ocean Report 2024, the message remains that observations and research is falling short and hence there is a lack of adequate and aggregated data. But as more states, industries and organizations realize that we need to measure in order to manage and protect marine ecosystems, we gradually get more data, get deeper into the issues, and can include new topics of research.

Every indication is, however, that the ocean crisis is developing faster than our knowledge of it. We therefore need to accelerate the mobilization which is under way in the UN Decade for Ocean Science for Sustainable Development 2021-30. We need to transform ocean science and our relationship to it. We need better knowledge as a basis for sustainable ocean planning and management, within and beyond areas of national jurisdiction. And we need a much stronger, much faster and more dynamic interplay between ocean knowledge, policy and action.

The StOR is intended to be complementary to multi-year assessments informing major international environmental conventions, such as the UN World Ocean Assessment, IPCC and IPBES. It is essential to keep the general public, industries and governments fully informed of the quickly evolving situation in the ocean, and what is being done. The StOR will also help to monitor the progress of the UN Decade of Ocean Science for Sustainable Development, 2021–2030, thus contributing to mobilizing global action towards 'ocean we need for the future we want'.

The 2024 StOR is the result of dedicated efforts on the part of leading experts in the broad family of ocean research. Without their time and engagement, the StOR would not be possible.

I offer my grateful thanks to all those who contributed their expertise, time and goodwill to the this edition. And I offer you, the reader, an important encounter with the State of the Ocean.

Vidar Helgesen

State of the Ocean Report — *Key Messages*

The State of the Ocean Report (StOR) has the ambition to inform policymakers about the state of the ocean and to stimulate research and policy actions towards 'the ocean we need for the future we want', contributing to the 2030 Agenda and in particular SDG 14, which reads 'Conserve and sustainably use the oceans, seas and marine resources', as well as other global processes such as the UNFCCC, the Convention on Biological Diversity and the Sendai Framework for Disaster Risk Reduction.

Structured around the seven UN Decade of Ocean Science for Sustainable Development Outcomes, the Report provides important information about the achievements of the UN Ocean Decade and, in the longer term, about ocean well-being. The StOR will be used to inform policy and administrative priorities and identify research focus areas that need to be strengthened or developed.

More than 100 authors from 28 countries contributed to the Report. The different sections provide insights on ocean-related scientific activities and analyses describing the current and future state of the ocean, addressing physical, chemical, ecological, socio-economic and governance aspects.

A clean ocean where sources of pollution are identified and reduced or removed

Continuous measurements show that eutrophication – excess nutrients in the ocean – persist and continue to increase. There is a need to better quantify the dominant sources of nitrogen (N) and phosphorus (P) across all large marine ecosystems to develop strategies and policies for their reduction.

Since the 1990s, the amount of plastics in the ocean has significantly increased and is trending to continue to increase at a worsening rate that will result in impacts that are beyond the safe operating space for humanity.

Global mechanisms to track the extent and distribution of nutrient and plastic pollution in our oceans are urgently required to support mitigation and adaptation strategies.

A healthy and resilient ocean where marine ecosystems are understood, protected, restored and managed

The ocean is continuing to act as a carbon sink, absorbing large amounts of carbon, which are predicted to increase ocean acidification by more than 100% by the end of the century. Adaptation and mitigation, however, will require national and subnational action, which can only be delivered once local and regional variations in ocean acidification and its impacts are understood.

At the same time, ocean warming from the surface down to the abyss is happening at an unprecedented pace and the rate is accelerating. The main and well-known consequences include rising sea levels, alterations in ocean currents and dramatic changes in marine ecosystems.

And as if that would not be sufficient to disturb the provision of ocean services, the ocean oxygen content is decreasing, resulting in worsening hypoxia and larger low oxygen areas. New research will be required to estimate the rate change and to predict the consequences.

Marine Protected Areas provide shelter for marine life against these stressors. More than 70% of endangered species are reported to seek shelter in Marine Protected Areas. These hotspots of marine biodiversity are crucial for supporting both food security and the overall health of our oceans now and in the future.

Another refuge against a warmer, more acidic ocean, which holds less oxygen are coastal blue carbon ecosystems (mangroves, seagrasses and tidal marshes). They continue to be an important store of carbon; however protection is not guaranteed and 20–35% have been lost since 1970.

Marine Spatial Planning is an important policy mechanism to help reduce the pressures on marine ecosystems. As of 2023, 126 countries and territories (a 20% increase since 2022) have applied area-based policies to sustainably manage activities in the ocean. The continuance of this positive trend will be an important contribution to action under SDG 14.

A productive ocean supporting sustainable food supply and a sustainable ocean economy

The world will see an additional 2 billion people in the next 25 years, adding pressure to already impacted food supplies on land and in the ocean. Aquatic foods are a major source of food with 182 million tonnes of aquatic animals and an additional 36 million tonnes of algae used for food and food production. Fisheries and aquaculture production continues to grow, reaching a record of 218 million tonnes in 2021. A deeper appreciation and understanding of the role that aquatic foods can play is essential to harness their unique capacity for addressing nutritional, social and environmental food system challenges in the future.

A predicted ocean where society understands and can respond to changing ocean conditions

After four decades of investment, global, regional and coastal operational ocean prediction systems have matured, providing accurate forecasts to diverse users. However, a significant inequality between the prediction capacity in the northern and southern hemispheres persists.

There is no doubt that the sea level is rising and that this will accelerate in the future. Melting ice masses from the Greenland and West Antarctica ice sheets and stronger ocean warming are contributing to the expansion of marine waters.

Even today, the ocean contains 40 times as much carbon as the atmosphere. Future climate scenarios are considering the potential of marine carbon dioxide removal techniques to increase this stock. A variety of techniques have been proposed, but large-scale deployment cannot be implemented without an increased understanding about how these new approaches will interact with ocean carbon cycle and marine ecosystems, their risks and benefits.

A safe ocean where life and livelihoods are protected from ocean-related hazards

Tsunamis are a major threat to human life, expected to intensify with climate change and rising sea level. They can cause extensive damage to critical infrastructure and homes, disrupt economies and livelihoods, and lead to loss of life, especially with the current growth in coastal population and tourism worldwide. Nearly 90% of tsunamis have been generated by large earthquakes or landslides triggered by earthquakes. Considerable efforts have now led to 150 countries and territories actively contributing to global efforts in tsunami hazard resilience by countries and territories. Despite these advances, tsunamis from non-seismic sources remain a key challenge to be addressed.

Similarly, harmful algae blooms continue to impact ocean ecosystems at an increasing rate amid rising seafood demand and coastal development. Among the approximately 10,000 species of marine phytoplankton in the world's oceans today, some 200 taxa produce toxins. Despite this risk to food security, identifying the drivers and causes remains challenging, as a global synthesis is lacking.

An accessible ocean with open and equitable access to data, information and technology and innovation

Observations of the ocean's physical, chemical and biological characteristics are the basis of sustainable development. To date, the Global Ocean Observing System comprises 8,000 observing platforms, operated by 84 countries through 300 programmes, delivering more than 120,000 observations daily. However, spatial and temporal observation gaps need to be closed to provide the information required for action.

For example, of the 120,000 daily observations, many are missing auxiliary information necessary to define quality and suitability, resulting in 10–15% of this data not being utilized. Cooperative efforts to align data reporting and access are required to increase use.

A prerequisite to ensure equitable global sharing of data and information is free and open access. Worldwide efforts, coordinated by IODE, have successfully led to the establishment of a global network of 101 data centres in 68 countries that cooperate to improve data access and interoperability. Further expansion of this network will continue to support greater information accessibility and useability as part of action under SDG14.

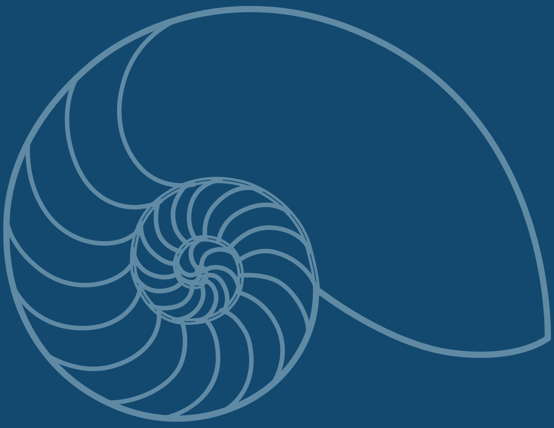
Additionally, greater global effort on increasing our knowledge of the seafloor is required, with more than 75% of the ocean floor remaining unmapped. New technologies and partnerships are, however, aiming to close this gap. Since 2022, 5.4 million km2 of new data, equating to an area twice the size of Argentina, have been obtained.

An inspiring and engaging ocean where society understands and values the ocean in relation to human wellbeing and sustainable development

Ocean literacy, an effort to increase the knowledge and understanding of the pivotal role of the ocean for human well-being and sustainable development, is an exciting global movement involving the efforts of hundreds of stakeholders in 2023. Future activities will aim to increase participation from the Southern Hemisphere, as more than 70% of ocean literacy efforts are taking place in the Northern Hemisphere.

The importance of the ocean in safeguarding lives now and in the future is no longer a topic addressed by ocean scientists alone. Non-academic partners are becoming increasingly involved in ocean science and observation. The ambition is to equip the global fleet, including container ships, fishing and leisure vessels with ocean sensors to exponentially increase ocean observations.

It is important to remember that Indigenous peoples have been observing, using and conserving the ocean and its resources for hundreds of years. These include peoples living at different latitudes, from the Arctic to the tropics. Their knowledge on maintaining the intricate balance between nature and humanity remains an important resource for researchers and policy-makers to draw upon. Increased effort is required to better engage Indigenous peoples in marine policy and planning to transition to 'the ocean we need for the future we want'.



A clean ocean, free of plastic pollution

Trends of eutrophication and alteration of nutrient ratios

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Introduction

The world's coastal ocean has experienced rapidly increasing inputs of plant nutrients nitrogen (N) and phosphorus (P) from land-based sources. The mobilization of these nutrients during the production of food, feed and other products in agriculture, aquaculture and through discharge of household and industrial wastewater has increased rapidly in recent decades (Beusen *et al.*, 2022; Seitzinger *et al.*, 2010), leading to increased plant and phytoplankton growth in many coastal waters. Increased plant and phytoplankton growth leads to oxygen depletion when oxygen consumption during decomposition of plant material exceeds oxygen exchange with the atmosphere, leading to temporary or permanent hypoxic conditions, as observed in an increasing number of sites (Breitburg *et al.*, 2018). At the same time, human activities have changed the proportion of different nutrients exported to the coastal zone (Beusen and Bouwman, 2022) (Figure 1), which can alter the types of plants and plankton that grow in fresh and coastal waters, sometimes causing toxic or otherwise harmful algal blooms (Glibert, 2020).

Findings: Status and trends

Alterations in the structure of food webs due to eutrophication are occurring in many coastal marine ecosystems with changes in the structure of benthic communities (Lim *et al.*, 2006) and act as stressors on biodiversity, plankton community structure and food webs (Borja *et al.*, 2016; Clark *et al.*, 2017; Holland *et al.*, 2023; Korpinen *et al.*, 2021). Coastal habitat loss is a global problem – for example, 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, but also 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 (Brzezinski, 1985; Redfield *et al.*, 1963). Non-diatom phytoplankton, often harmful, species like dinoflagellates may develop in waters where N and P are available in excess relative to the diatom Si demand, a condition expressed by the Indicator for Coastal Eutrophication Potential (ICEP) (Billen and Garnier, 2007) (Figure 2). ICEP has been proposed as the indicator for Sustainable Development Goal 14.1.1a on eutrophication, which is to: By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution.

Non-diatom phytoplankton species are generally of lower food quality and less grazed upon than diatoms; consequently a larger fraction becomes detritus and as a result there is substantial oxygen demand upon settling and degradation (Cloern, 2001; Officer and Ryther, 1980). Many non-diatom phytoplankton species causing high biomass and sometimes harmful blooms proliferate under conditions of elevated N:P conditions (Glibert *et al.*,

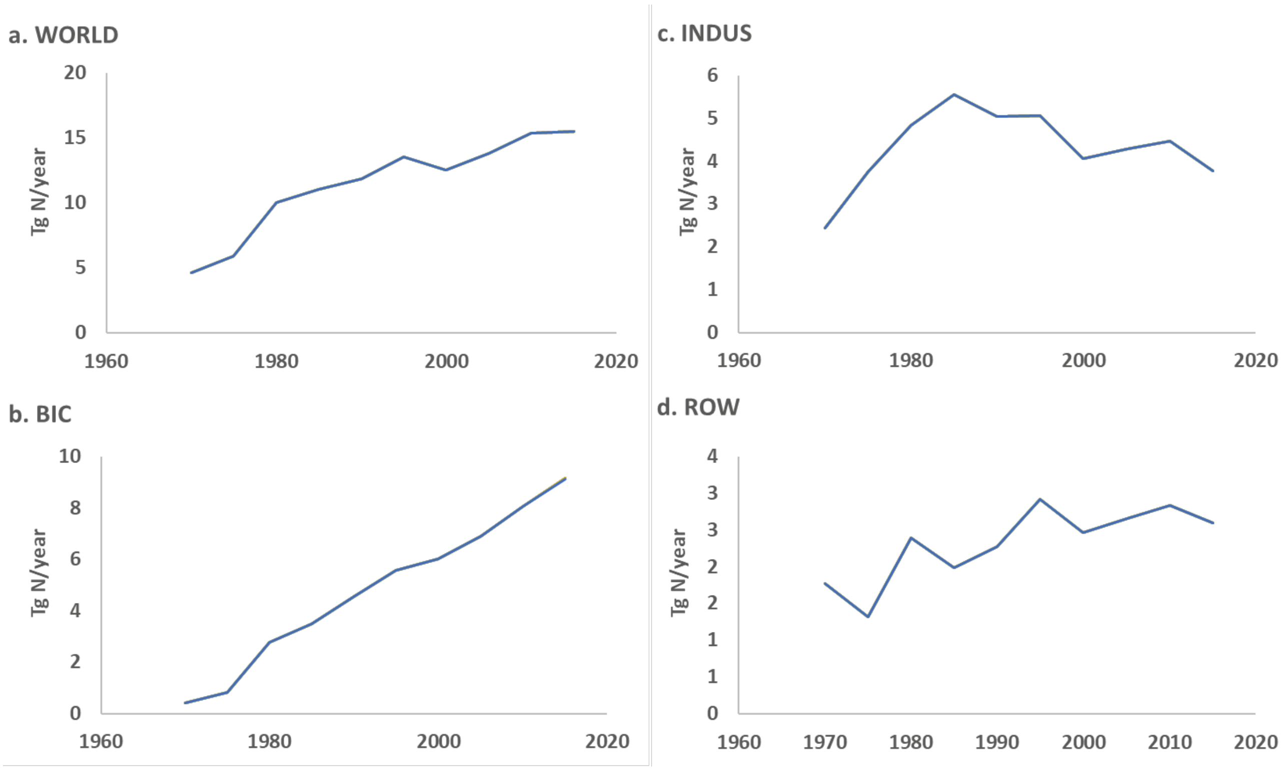

Figure 1. River N export for rivers with >50% anthropogenic sources and N:P ratio >25. By including only rivers with strong human influence, rivers such as the Amazon with a dominant natural signature and with high Si load relative to N and P are excluded. INDUS = industrialized countries (North America, Europe, Japan, Oceania), BIC = Brazil, India, China, ROW = rest of the world. *Source*: (Beusen and Bouwman, 2022).

2014). Currently, many global rivers are experiencing a trend of increasing nutrient loads, with rising N:P ratios and either stable or declining silicon (Si) loads. However, an exception to this trend is the North Sea, where both N and P loads are decreasing but N:P ratios are increasing (Beusen and Bouwman, 2022; Devlin *et al.*, 2023). At the global scale, 36% of the total N export to coastal waters is from rivers dominated by anthropogenic sources and with N:P ratios exceeding the Redfield ratio (Figure 1). Additional N comes from submarine groundwater discharge in many coastal waters (Beusen *et al.*, 2013; Slomp and Van Capellen, 2004), at times even exceeding river inputs (Santos *et al.*, 2021). While in industrialized countries the anthropogenic N load with high N:P has been declining in recent years, in other parts of the world N:P ratios are still steadily increasing, particularly in the Brazil, India, China (BIC) region (Figure 1). Coastal waters receiving discharge from rivers draining the most densely populated countries of the world (India and China) show the highest eutrophication risk of harmful algal blooms and hypoxia (Figure 2).

In addition to the distortion of nutrient ratios, a shift in the nutrient composition, particularly towards more organic (as opposed to inorganic) N and P forms, may lead to the proliferation of specific harmful algal species (Glibert, 2017). It is known that urea fertilizers, the world's most common N fertilizer, contribute substantially to river dissolved organic N (Glibert *et al.*, 2006). Reservoirs can also play a role in nutrient transformations and coastal nutrient delivery by preferentially retaining inorganic N and P forms (Ou *et al.*, 2018; Wang *et al.*, 2011).

Finally, there is mounting evidence that climate change will exacerbate eutrophication and its associated negative impacts through multiple processes (Meerhoff *et al.*, 2022; Paerl and Paul, 2012; Rabalais *et al.*, 2009). One of the primary mechanisms through which climate change influences eutrophication is by enhancing vertical water column stability due to increased density stratification caused by climate-driven changes in surface temperatures and salinities. This condition fosters the formation and proliferation of some HABs (Michalak, 2016). Furthermore, potential interactions between ocean acidification and coastal eutrophication are being investigated, although these relationships remain largely uncertain (Kessouri *et al.*, 2021). Major causes of this uncertainty are the interactions between coastal eutrophication and other ongoing human-driven changes in coastal waters.

Some non-diatom phytoplankton species may be harmful or even toxic. HABs can produce toxins that can cause massive fish kills or cause ecological damage through the development of hypoxia or anoxia and other habitat alterations, with a series of important negative

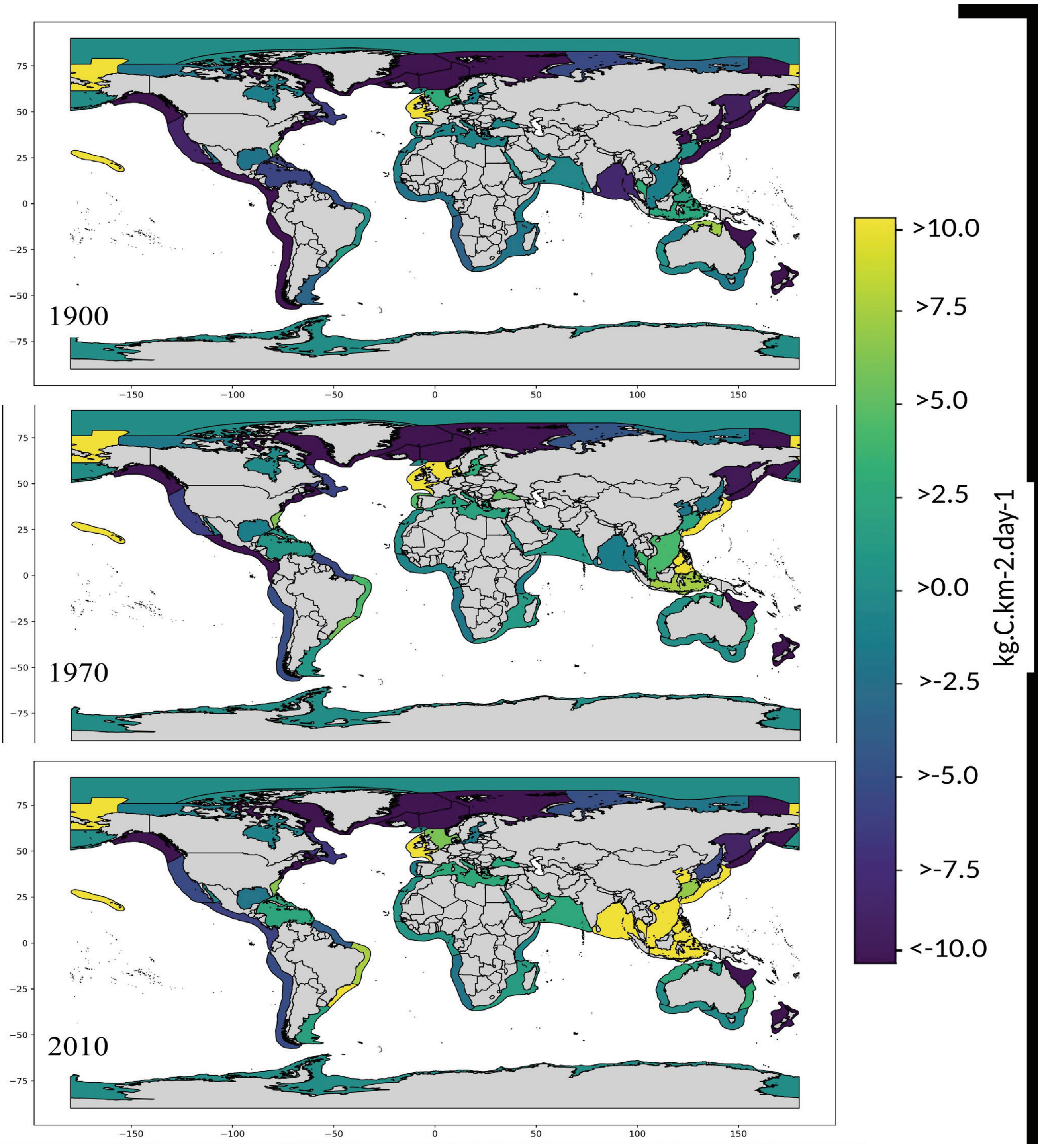

Figure 2. Indicator of Coastal Eutrophication Potential (ICEP) values for coastal river inputs aggregated to the scale of LMEs for years 1900 (top), 1970 (middle) and 2010 (bottom). ICEP is calculated as the excess of N or P over the requirement of diatoms based on the Redfield ratio and is expressed as the potential growth of non-diatom species in kg C-equivalents per km^2 per day (Beusen and Bouwman, 2022; Liu *et al.*, 2020). High values suggest a high potential for the formation of HABs. Pronounced increases in ICEP have occurred over time, particularly in South and Southeast Asia and off the coast of eastern South America. *Source*: Authors' compilation.

consequences for human health, economy, society and recreation. Many international research efforts since the start of the Global Ecology and Oceanography of HABs (GEOHAB) programme (Cullen, 1998; GEOHAB, 2006) have contributed to a growing consensus that coastal eutrophication, combined with climate change, is contributing to the apparent worldwide increase in the frequency and areal extent of coastal HABs (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, while also affecting shellfisheries and human health. It should be noted, however, that not all geographic regions and not all HAB species respond in a uniform manner to eutrophication and climate change (see 'Harmful algal bloom impacts increase amid rising sea food demand and coastal development').

Conclusions and next steps

We need to better quantify the dominant sources of N and P across all large marine ecosystems to develop strategies and policies for their reduction. From the above, it is clear that strategies and policies to reduce nutrients need to be balanced. Controlling loads of P without concomitant strategies to control N may lead to unexpected and unwanted impacts such as HABs (Glibert, 2017). The escalating global nutrient cycles and distortion of nutrient ratios under continuing global warming underscores the urgency to develop approaches to examine interactions among these disturbances and to incorporate ecological principles into management and restoration of coastal environments.

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Status and trends of plastic pollution, including strategies on how to reduce them

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Introduction

Plastics have become integral to many industrial and societal functions since widespread industrial production, starting in the 1950s. The rapid increase in plastic production resulted in uncontrolled leakage into the environment. Reports of plastic pollution in the ocean started to emerge in the late 1960s but remained rather a niche interest. However, in the past two decades, the pervasive and ubiquitous presence of plastics in marine ecosystems has become better documented, revealing complex environmental, social and economic impacts (MacLeod *et al.*, 2021). The global extent of plastic pollution has led some researchers to conclude that the impact of plastics is beyond the safe operating space for humanity (Persson *et al.*, 2022). A major challenge in the coming decade will be to identify and implement measures to ensure sustainable and transparent plastic production, restrict the generation of plastic waste, prevent further leakage into the ocean, and carefully remediate affected ecosystems.

Findings: Status and trends

The distribution, behaviour, and impacts of marine plastic litter and microplastics have become a major research area, attracting researchers from a wide variety of natural and social sciences, as well as engaging environmental NGOs, citizen's groups, industry, governments, and IGOs. Research ranges from laboratory-based experiments and small-scale descriptive studies to attempts to provide a global perspective. For example, it has been estimated that there are over 170 trillion plastic particles floating in the ocean, based on data from 11,777 stations, weighing between 1.1 and 4.9 million tonnes (Figure 3; Eriksen *et al.*, 2023). The authors observed no detectable trend in abundance until 1990 and then, after a period of fluctuating concentrations, a rapid increase from 2005 until present. In another development, the output from a GESAMP international workshop highlighted the importance of the atmospheric transport of micro- and nano-plastics, and exchanges across the ocean atmosphere interface (Allen *et al.*, 2022). The authors estimated that 0.013–25 million metric tons per year of micro-(nano-) plastics may be deposited in the ocean via atmospheric transport alone.

Observations of macro-litter are still rather limited, apart from shoreline surveys. However, some of the gaps in ocean observations are being filled; for example, one study revealed the distribution of seafloor litter around the Atlantic and Indian Ocean coasts of Africa and in the Bay of Bengal, based on litter recorded as by-catch in demersal trawl surveys for fisheries resources (Buhl-Mortensen *et al.*, 2022). This represents one component of the EAF-Nansen Programme, an endorsed Ocean Decade Action. This study supported previous findings that abandoned, lost, or otherwise discarded fishing gear (ALDFG) can constitute a significant proportion of seafloor litter in areas of higher fishing effort, such as seamounts (Pham *et al.*, 2014). Elsewhere, seafloor macro-litter appears to be dominated by single-use plastic items, including at abyssal depths (Chiba *et al.*, 2018).

The current annual production of plastics (approximately 450 million tonnes) is predicted to double by 2045, under current trends. The inadequacy of waste management to meet this demand is a particular problem for developing countries, and especially Small Island Developing States (SIDS), with poorly developed waste infrastructure. Export of plastic waste can exacerbate the problem for the receiving countries, increasing the risk to marginalized and vulnerable communities. Efforts to reduce waste generation and improve waste management continue to make some progress. The GloLitter Partnerships Project aims to reduce sea-based sources of plastic waste, principally from the shipping and fishing sectors. GloLitter is being implemented by IMO and FAO and provides support for developing countries, including SIDS and Least Developed Countries.

In addition to waste reduction and litter prevention, environmental clean-ups may be justified, provided these are carefully targeted and designed to minimize further harm (Bergmann *et al.*, 2023; Falk-Andersson *et al.*, 2023). Developments in risk assessment methods for both macro- (Roman *et al.*, 2022) and micro- (Mehinto *et al.*, 2022) plastics will help to target appropriate responses. The Digital Platform of the Global Partnership on Plastic Pollution and Marine Litter provides a repository of technical and other resources.

Conclusions and next steps

Working Group 1 (Clean Ocean) of the Vision 2030 process

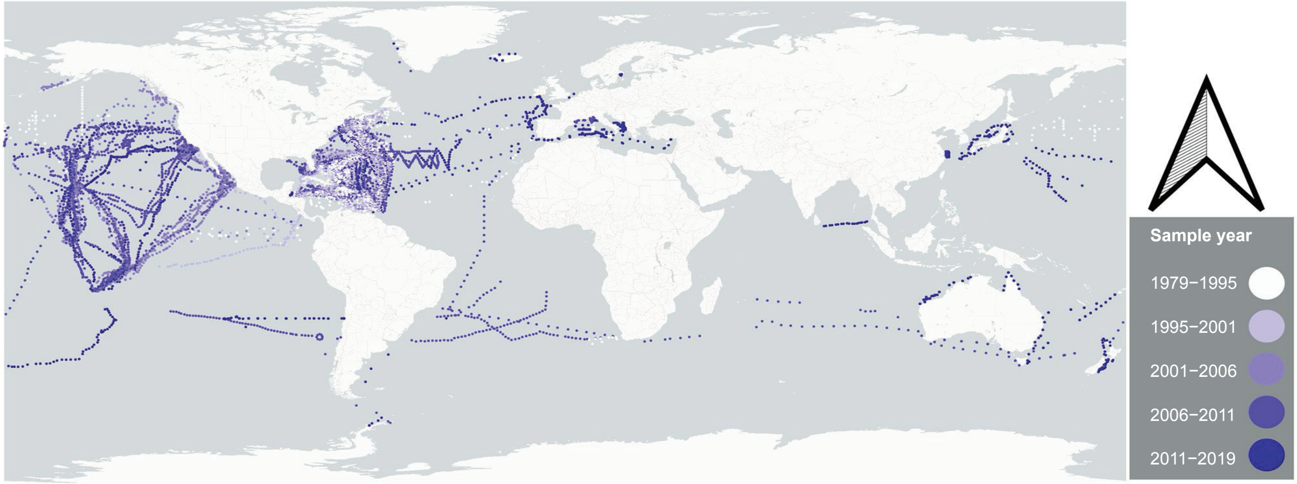

Figure 3. The distribution of sampling stations, 1979–2019, used to estimate the total quantity of floating plastic particles in the ocean. *Source*: Eriksen *et al.* (2023).

of the UN Decade of Ocean Science for Sustainable Development comprises experts from a wide range of disciplines and geographic regions, and is supported by Back to Blue, a joint initiative of Economist Impact and the Nippon Foundation. A draft White Paper was completed in early 2024, outlining 'a set of strategic ambitions to address the most pressing gaps in science, knowledge and solutions needed to achieve a clean ocean by 2030', with plastic pollution a key component. The final version was presented in a Science Solution Forum at the Ocean Decade Conference in Barcelona, in April 2024.

Sustained, comprehensive and global actions are needed to reduce the generation of plastic waste and prevent unavoidable plastic waste from leaking into the environment. Critical examination of effective policy options (Economist Impact, 2023; Ferraro and Failler, 2020) provides essential input to current negotiations towards an international binding instrument on plastic pollution (UNEP/INC Secretariat, 2023).

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Additional resources

Back to Blue. Caring for the Ocean, an initiative of Economist Impact and The Nippon Foundation. https://backtoblueinitiative.com/

Global Partnership on Plastic Pollution and Marine Litter (GPML) Digital Platform https://digital.gpmarinelitter.org/knowledge/library/map

GloLitter Partnerships Project https://glolitter.imo.org/

UN Decade of Ocean Science Working Group 1 – Clean Ocean https://oceandecade.org/news/vision-2030-wg1-takes-collaborative-effort-to-assess-and-mitigate-marine-pollution/

A healthy and resilient ocean where marine ecosystems are understood, protected, restored and managed

Status and trends of ocean acidification

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Introduction

The ocean absorbs around one-quarter of the annual emissions of anthropogenic carbon dioxide (CO_2) to the atmosphere (WMO, 2023), thereby helping to alleviate the impacts of climate change on the planet (Friedlingstein *et al.*, 2023). The cost of this process to the ocean is high, as the absorbed CO_2 gas 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 seawater pH. Ocean acidification threatens marine organisms and ecosystem services, including food security, by reducing biodiversity, degrading habitats and endangering fisheries and aquaculture. Ocean acidification will continue to increase with high confidence (IPCC, 2021)) as 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. As the acidity of the ocean increases, its capacity to absorb CO_2 from the atmosphere decreases, impeding the ocean's role in moderating climate change (IPCC, 2019).

Findings: Status and trends

Global efforts are under way 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, 539 stations in 41 countries in 2023; 638 in 2024: Data collected by IOC-UNESCO, Figure 4), the current coverage is inadequate, with time series not long enough to determine trends and data gaps due to lack of observations found in all areas.

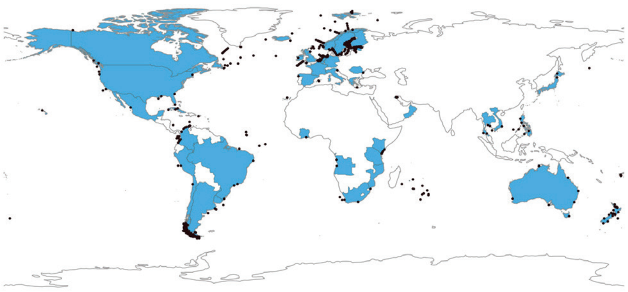

Figure 4. Map illustrating surface ocean carbonate chemistry measurement locations received by the IOC for SDG 14.3.1 ocean acidification reporting. Blue: countries whose data was reported in accordance with the SDG 14.3.1 Indicator Methodology. Black dots: location of sampling stations from which data was collected (638 stations in 2024). *Source*: IOC-UNESCO.

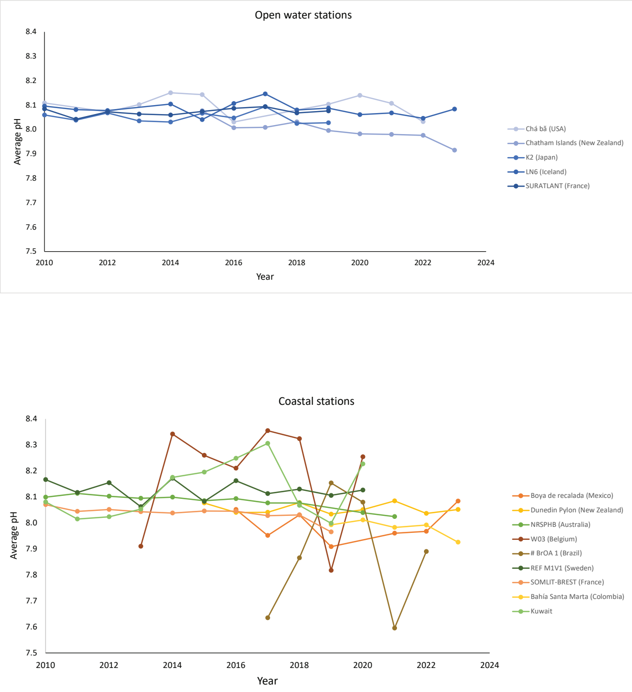

Figure 5. Variations in the annual average pH values from a suite of representative sampling stations in open and coastal waters. Data from IOC/UNESCO, SDG14.3.1 ocean acidification reporting.

Notes: Open water stations: Chá bă – USA, Pacific Ocean (data from 2010-2022); Chatham Island – New Zealand, South Pacific Ocean (data from 2015–2023); K2 – Japan, North Pacific Ocean (data from 2010–2019); LN6 – Iceland, Iceland Sea, North Atlantic Ocean (data from 2010–2023); SURLATLANT – France, Atlantic Ocean (data from 2010–2019).

Coastal water stations: Boya de recalada – Mexico, Pacific Ocean (data from 2016-2023); Dunedin Pylon – New Zealand (data from 2015–2023); NRSPHB – Australia, National Reference Station Port Hacking station (data from 2010–2021); W03 – Belgium, Scheldt Estuary (data from 2013–2020); # BrOA1 – Brazil, Reference Station (data from 2017–2022); REF M1V1 – Sweden, Reference Station (data from 2010–2020); SOMLIT-BREST – France, Celtic Sea (data from 2010–2019); Bahía Santa Marta – Colombia, Caribbean Sea (data from 2019–2023); Kuwait – Kuwait Bay (data from 2010–2020).

Source: IOC-UNESCO.

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 4), with an average global surface ocean pH decline of 0.017–0.027 pH units per decade since the late 1980s. In contrast, observations of ocean acidification from coastal areas present a more varied picture (coastal data: Figure 5). In addition to absorbing atmospheric CO_2, these coastal areas are subject to a wide range of additional processes affecting the carbonate chemistry of the water. Coastal ocean acidification can be caused by natural processes, such as freshwater influx, biological activity, temperature change and large ocean oscillations (such as the El Niño/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO)), or human activities including nutrient input from agricultural and industrial activities. Due to this natural variability, longer term data sets are needed for coastal areas than for the open ocean in order to determine the time of emergence of ocean acidification trends; observations should include those other parameters that can affect carbonate chemistry in coastal areas. The latest OSPAR Quality Status Report (McGovern *et al.*, 2023) on ocean acidification has observed that overall pH is declining at faster rates in the shallow coastal regions than in the open ocean due to these additional stressors and processes. This is of particular relevance as most of the ocean's biodiversity is found in the coastal zones.

Conclusions and next steps

More and better distributed long-term observations of coupled 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.

While there is clear evidence of the impacts of ocean acidification on marine organisms and ecosystems, the identification of the precise impacts at relevant temporal and geographical scales to the affected organisms, and the attribution of impacts to acidification, remain a challenge. The GOA-ON biological working group, co-led by IOC, is spearheading efforts to establish agreed methodologies for the observation of ocean acidification impacts on organisms and ecosystems (Widdicombe *et al.*, 2023). Integrating these observations with forecasting models will improve the understanding of the trends, patterns, drivers and biological impacts of ocean acidification now and in the future.

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Additional resources

Global Ocean Acidification Observing Network http://goa-on.org

IOC SDG 14.3.1 portal http://oa.iode.org

Ocean Acidification Research for Sustainability Ocean Decade Programme http://goa-on.org/oars/overview.php

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Ocean warming

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Introduction

As assessed in the recent IPCC report, the global ocean is warming from the surface down to the abyss at an unprecedented pace, which is a direct consequence of anthropogenic global warming (IPCC, 2021; Cheng *et al.*, 2022). Globally, ocean warming provides the fundamental measure of Earth system heating in the climate system from anthropogenic forcing (von Schuckmann *et al.*, 2023). At the regional scale, ocean warming has wide-reaching implications (Cheng *et al.*, 2022). For example, ocean warming contributes to about 40% of the observed global mean sea-level rise and alters ocean currents (Gulev *et al.*, 2021). It also indirectly alters storm tracks (IPCC, 2018), increases ocean stratification (Li *et al.*, 2020) and can lead to changes in marine ecosystems (Bindoff *et al.*, 2019). Particularly, and together with ocean acidification and deoxygenation, ocean warming can lead to dramatic changes in ecosystem assemblages, biodiversity loss, population extinction, coral bleaching, infectious diseases and changes in animal behaviour (including reproduction), as well as the redistribution of habitats (García Molinos *et al.*, 2016; Gattuso *et al.*, 2015; Ramírez *et al.*, 2017). It is hence essential to provide regular data and information on the evolution and regional distribution of ocean warming and its impacts on seascapes to support the decade challenge for a healthy and resilient ocean where marine ecosystems are understood, protected, restored and managed (Ryabinin *et al.*, 2019).

Findings: Status and trends

Ocean warming can be derived from direct measurements of subsurface ocean temperature relying on different measurement platforms like direct shipboard observations, or autonomous instruments (Cheng *et al.*, 2022). Since 2005, technical evolutions under the international Argo programme achieved near-global ocean subsurface temperature sampling coverage from the surface down to 2,000m depth (Riser *et al.*, 2016) – a period which is often referred to as the golden period for global climate studies (von Schuckmann *et al.*, 2016). Ocean warming estimates during the historical dimension before the Argo era (i.e. from 2005 when Argo reached targeted near-global sampling coverage), reaching back to about the 1960s, is characterized by spatially and seasonally inhomogeneous sampling, including a strong interhemispheric bias favouring the northern areas in some estimates (Cheng *et al.*, 2022; Gulev *et al.*, 2021; Abraham *et al.*, 2013). Before Argo, the major instrumentation relies on shipboard techniques, which are known to be affected by instrumental biases, for which the international community has developed different solutions (Boyer *et al.*, 2016; Cheng *et al.*, 2016; Good *et al.*, 2011; Cowley *et al.*, 2013; Wjiffels *et al.*, 2009; Ishii and Kimoto, 2008). The international community has developed various methods and approaches to provide global-scale estimates from these measurements, and uncertainty could be largely reduced over the past decade through fundamental advancements in science (e.g. Cheng *et al.*, 2022; Hosoda *et al.*, 2008; Good *et al.*, 2013; Lyman and Johnson, 2014). However, given the limitation of the observing system, particularly during the historical era before 2005, inconsistencies remain, and reconciling the different estimates remains an essential approach (Johnson *et al.*, 2022; Gulev *et al.*, 2021; von Schuckmann *et al.*, 2023; Cheng *et al.*, 2022). In addition, satellite-based indirect estimates of full-depth ocean warming have been developed from the year 1993 onwards (Hakuba *et al.*, 2021; Marti *et al.*, 2022).

The upper 2,000m of the ocean continued to warm in 2023 at a rate of 0.32 ± 0.03 W/m^2 since 1960 (Figure 6) and it is expected that it will continue to warm in the future, causing changes that are irreversible on centennial to millennial time scales (IPCC, 2021). Over the past two decades, the rate of ocean warming has increased to 0.66 ± 0.10 W/m2 – a doubling which is extensively discussed in the scientific community (Loeb *et al.*, 2021; Minière *et al.*, 2023; Cheng *et al.*, 2024a; von Schuckmann *et al.*, 2023). At the regional scale, 2023 had been marked by unusually high values of ocean heat content as compared to the long-term state (Figure 7). The Tropical Atlantic Ocean, the Mediterranean Sea and the Southern oceans recorded their highest OHC observed since the 1950s (Figure 7; Cheng *et al.*, 2024b). Global ocean warming has been enhancing the regional marine heatwave (a period of abnormally high ocean temperatures relative to the average seasonal temperature in a particular marine region), with extremely high temperature values occurring frequently in many regions (e.g. Frölicher *et al.*, 2018).

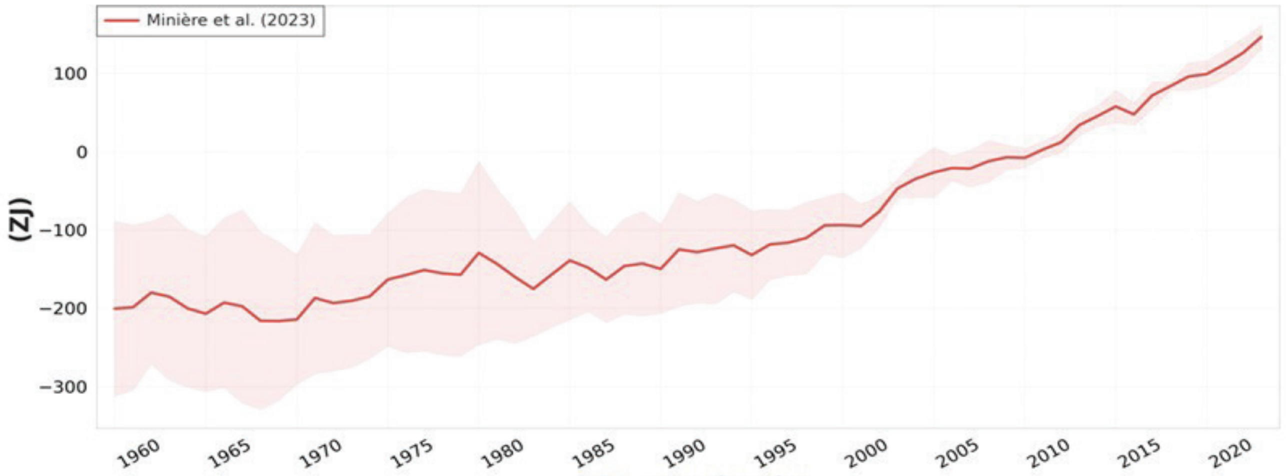

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Figure 6. Global mean ocean heat content from 1960–2023 (in ZJ) for the upper 2,000m depth as derived as an ensemble mean approach considering several subsurface temperature products and its uncertainty (shaded). *Source*: Minière *et al.* (2023).

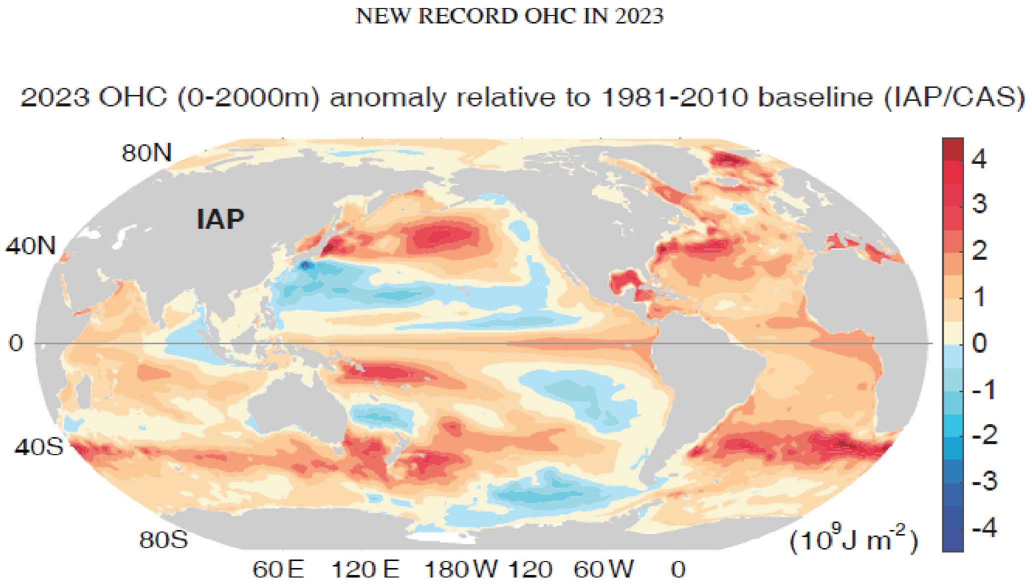

Figure 7. The annual OHC anomaly in 2023 relative to a 1981–2010 baseline for IAP/CAS data; units: 10^9 J m−2. *Source*: Cheng *et al.* (2024*b*).

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Global ocean deoxygenation: Status and challenges

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Introduction

Dissolved oxygen (O2) is required to sustain aerobic ocean life and oxidation of organic matter. Its distribution in the open ocean and coastal regions is sensitive to natural biogeochemical and physical processes that are being increasingly impacted by the ocean uptake of excess Earth energy imbalance (EEI) from the addition of human-induced greenhouse gasses (e.g. CO_2, CH4 and N2O) and excess nutrient inputs. About 90% of the EEI is being absorbed by the ocean, resulting in a cumulative increase in ocean heat content (OHC), mostly contained in the upper 2,000 m of the water column (von Schuckmann et al., 2022). The OHC gained can impact ocean overturning circulation, upper ocean stratification and lower the preformed O2 content of near-surface high latitude waters, reaching the interior deeper ocean through ventilation. Near-surface thermal stratification intensification weakens vertical mixing and the vertical flux of generally nutrient-richer deeper waters into the euphotic zone that fuels biologically mediated O2 production. The reduction in ocean O2 loss (i.e. O2 inventory, OI) has been termed ´deoxygenation´. While ocean deoxygenation would not affect the much larger atmospheric O2 inventory, it can have long-term negative impacts on the health of coastal and large marine ecosystems, a sustainable blue economy and coastal communities that depend on the ocean (e.g. tourism, fisheries, aquaculture, ecosystem services and marine protected areas). Nutrient over-enrichment of coastal areas results in deoxygenation and the emergence of hypoxia zones.

Findings: Status and trends

Deoxygenation results from a combination of climate change impacts and feedback mechanisms that are not well understood and quantified. More observations, particularly in the Southern Hemisphere, data synthesis and modelling efforts, are needed to assess the relative impact of factors causing ocean deoxygenation superimposed on natural low-frequency variability. Here, we describe some of the challenges associated with resolving deoxygenation trends and uncertainties.

Observation-based global ocean deoxygenation estimates require the aggregation and analysis of in situ O2 data that have been collected worldwide over several decades using different water samplers, methods and unit reporting protocols. While O2 is a frequently sampled essential ocean variable, its global 4-D (time, depth, latitude and longitude) coverage and data quality (e.g. precision, reproducibility, accuracy and uncertainty) are not well quantified. All O2 measurements in the instrumental record include some measurement error. Thus, the analysis of compiled O2 observations require an internally consistent, reproducible and quantifiable quality control (QC) assessment of the time-variant quality of the measurements.

Since the 1900s, O2 measurements have been obtained using modifications of the Winkler (1888) titration method. Carpenter (1965) indicated that the accuracy of the method using O2-saturated water is ~0.1%, or about ±0.22 µmol•kg-1. The shipboard measuring precision of high-quality data collected since the 1980s in relatively O2-rich deep waters is in the range of about ± 0.15 to 0.87 µmol•kg-1 (Saunders, 1986; Langdon, 2010). In the mid 1980s, different types of O2 sensors have been mounted on CTD frames, buoys, underway systems and, more recently, on gliders and Argo and BGC Argo floats. The sensors have a precision of ⩾ ± 2 µmol•kg-1 range (Grégoire et al. 2021). It is not the scope of this brief note to quantify all potential sources of error. One pressing problem is that the accuracy of the data collected is difficult to quantify directly because absolute or adopted reference standards have not been in use over time.

The ocean OI varies as a function of depth and basin (Figure 8). The 0–5,500 m depth global ocean OI is ~238.2 Pmol (Garcia et al., 2023). What is the net global ocean OI loss in the past decades? Global deoxygenation trend estimates vary significantly between observational studies. Schmidtko et al. (2017) reported a negative trend of about 0.96 ± 0.43 Pmol•decade-1 (1960–2014); Ito (2022) indicated a negative trend of 0.33 ± 0.05 Pmol•decade-1 (1965–2015); Roach and Bindoff (2023) indicated a global ocean loss of 0.84 ± 0.42% for the 1970–2010 time period (about 0.35 ± 0.18 Pmol•decade-1 assuming an OI of 238.2 ± 1.1 Pmol). The trends suggest approximate OI losses after 60 years of 0.83 to 2.42% (equivalent to about 1.43 to 4.15 µmol•kg-1 . Resolving such OI changes requires QC O2 data spanning several years and high 4-D coverage. Different ocean regions and depths can have different trends and OI losses.

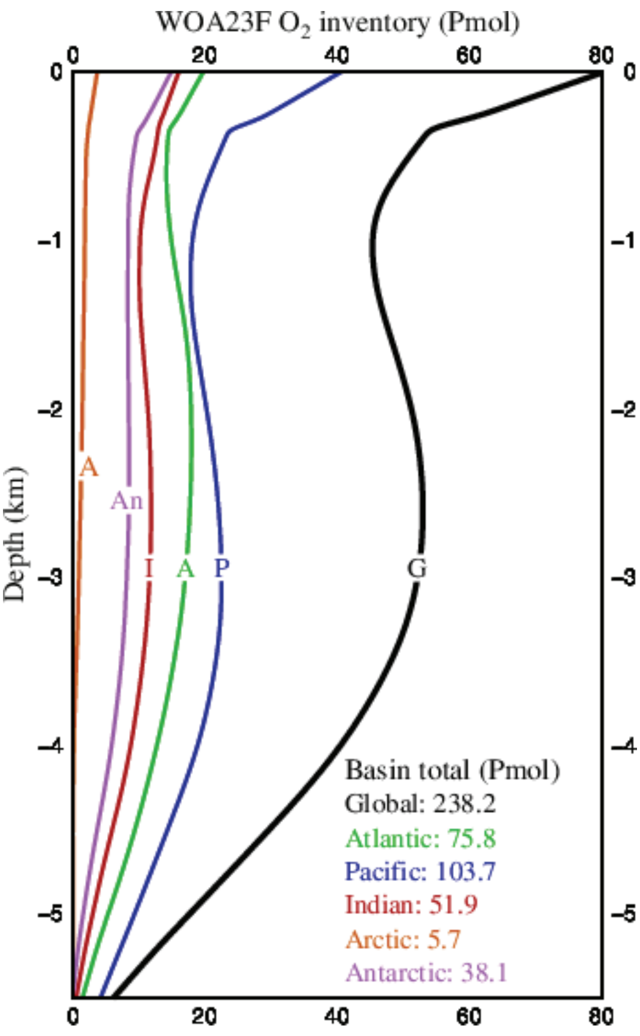

Figure 8. Ocean OI (Pmol) as a function of depth. *Source*: World Ocean Database.

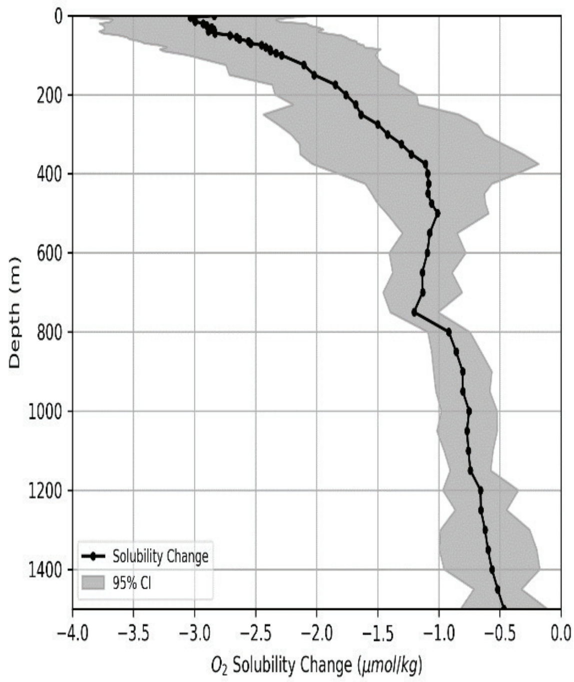

Figure 9. Global mean O2 solubility content decrease as a function of depth after 60 years. *Source*: World Ocean Database.

Comparing, and independently reproducing, published deoxygenation trends is difficult. Each study uses different baseline time periods, data compilations, data QC metrics and mapping algorithms (e.g. grid size and data gap treatment). One initial step to help quantify differences between the mappings could be conducting an international intercomparison exercise using common reference data.

The global ocean mean O2 solubility content loss attributable to ocean warming alone is relatively small when compared to the net OI loss. Figure 9 shows an estimate of O2 solubility loss (0–1,500 m depth) after 60 years due to ocean warming alone (Garcia et al., 2024. The global mean solubility estimated loss varies from about 0.5 to 3.1 µmol•kg-1.

Conclusions and next steps

The trends suggest a relatively rapid ocean response to recent climate change with potentially long-term negative impacts on the health and sustainability of coastal and large marine ecosystems. What is unclear is whether deoxygenation is accelerating in response to OHC increases (Li et al., 2023). The use of machine learning and artificial intelligence to potentially gain additional insight seems promising (Sharp et al., 2022). Developing international QC best practices and standards remains an issue (Grégoire et al., 2021). Public engagement and communication are needed for science-based informed policy decision-making, societal adaption and sustainable blue economy strategies.

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Biodiversity knowledge and threats on marine life: Assessing no-take zones as a refuge for marine species

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Introduction

In our preceding StOR section entitled 'New knowledge on and threats to marine biodiversity' (Costello *et al.*, 2022), our emphasis lay on elucidating the existing state of biodiversity knowledge. In this chapter, our focus shifts towards the conservation status of marine biodiversity. The UN 2030 Agenda for Sustainable Development advocates for heightened protection of marine biodiversity to ensure sustainable food security. This aligns with the targets outlined in the Kunming-Montreal Global Biodiversity Framework under the Convention on Biological Diversity, to protect 30% of the ocean by 2030, emphasizing both conservation (Targets 1, 2, 3 and 4) and sustainable resource utilization (Targets 5, 9, 10 and 11), as well as ensuring knowledge is accessible (Target 12). To monitor progress, we provide statistics on the total number of marine species, and those most vulnerable to extinction, within designated Marine Protected or Managed Areas (MPA) as of now.

We used a definition of MPA-based areas where regulations impose significant restrictions on fishing compared to adjacent regions (excluding areas that are not protected from fishing), denoted by protection scores of 3 (partly protected, n = 1,865 and 5.9 % of ocean area), 4 (very limited to fishing, n = 968 and 1.2 % of ocean area) and 5 (no fishing, n = 4,201 and 2.4 % of ocean area) (total n = 7,034) (Protected Seas, 2024). This classification of areas is focused on the dominant threats to marine species, habitats and food webs and is based on direct assessment of national management regulations. This avoids ambiguity where places may be called MPA but may or may not allow different human activities. Due to some overlap of MPA boundaries, when combined, they constitute 9.0 % of the entire ocean (comprising 2.8 % of the high seas and 18.7 % of the country's Exclusive Economic Zones). To conduct our analysis, we downloaded and indexed marine species distribution data sourced from the Ocean Biodiversity Information System[1] and the Global Biodiversity Information Facility[2].

Findings: Status and trends

Number of marine species within MPA

As of now, a total of 93,106 marine species have been documented within the MPA. These records encompass nearly 50 million distribution data points, and half were recorded in the past eight years. Looking at higher-level taxonomic groups (Figure 10), most species of marine turtles and seabirds and more than 50% of fish, sharks, rays and mammals have reported occurrence records that fall within at least one current MPA. Nevertheless, a substantial portion of marine life lacks designated refuge areas (level 2 or less).

Number of threatened marine species within MPA

Among the 1,473 marine species listed on the global IUCN Red List as being at risk of extinction, specifically categorized as Vulnerable (VU), Endangered (EN) and Critically Endangered (CR), 1,061 (72%) are currently reported within at least one MPA. These figures diminish to 912 (62%), 622 (42%) and 794 (54%), for each MPA category 3, 4 and 5, respectively. Based on known occurrences, we calculated the fraction (%) of the species' distribution range (habitat) that falls within the MPA coverage. For the majority of those threatened species, only a small fraction (median 7%) of their distribution as reported in OBIS is covered by MPA areas (Figure 11).

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[1] See. Ocean Biodiversity Information System. Intergovernmental Oceanographic Commission of UNESCO: https://www.obis.org.

[2] See Global Biodiversity Information Facility:https://www.gbif.org.

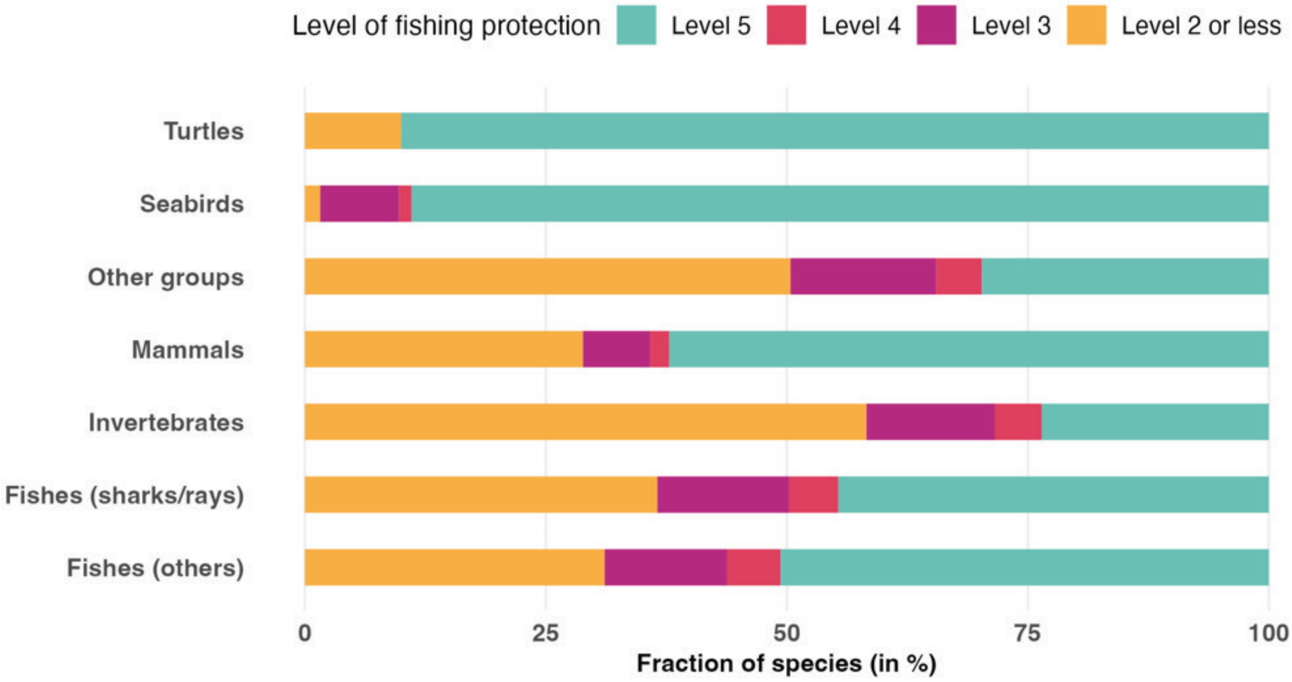

Figure 10. Fraction of marine species in the MPA by higher-level taxonomic groups. We consider MPA those with a level of fishing protection higher than 3. Thus, the fraction in level 2 or less includes species in areas with negligible or no protection (i.e. not in MPAs). *Source*: OBIS/IOC-UNESCO.

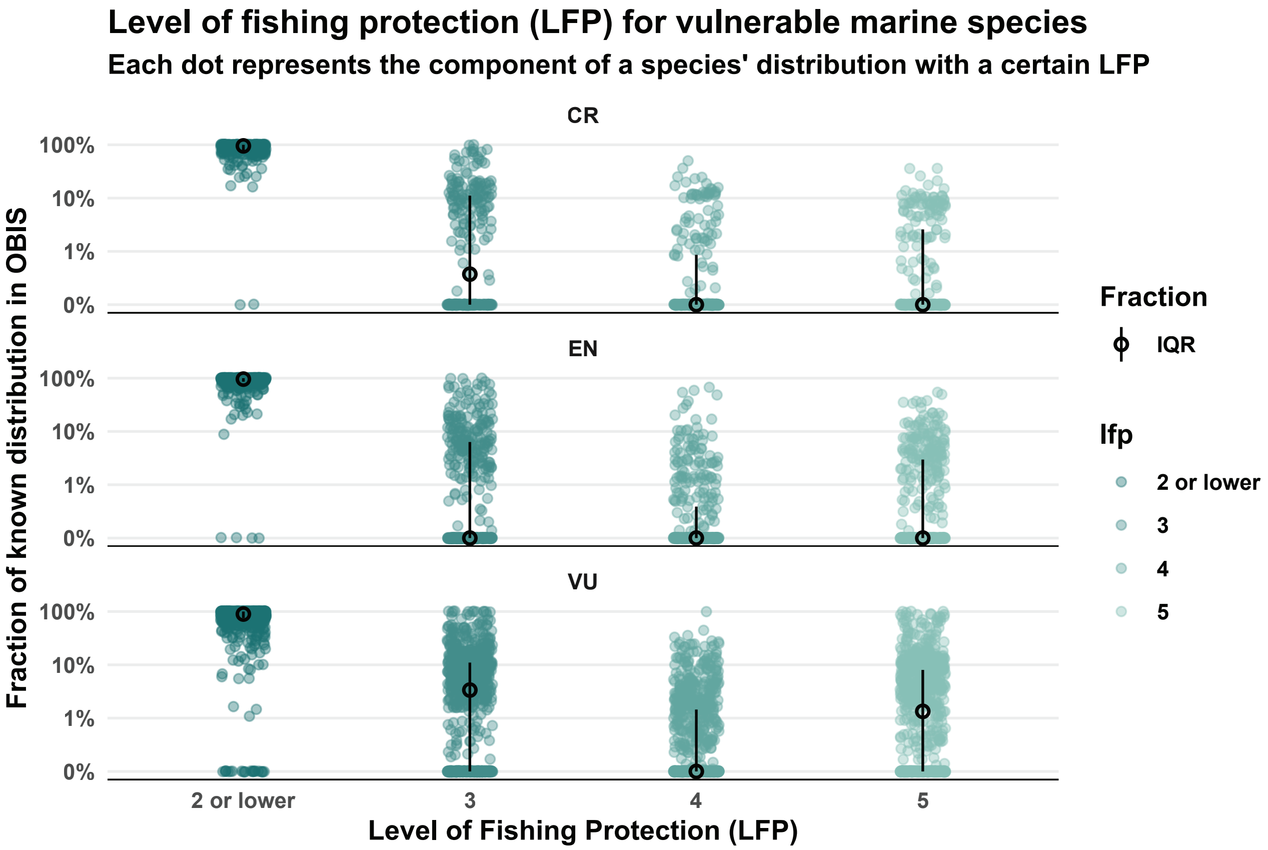

Figure 11. Level of protection for threatened marine species (IUCN red list categories CR, EN, VU). Each dot represents the percentage of a species' distribution in OBIS within a certain MPA level of protection from fishing. *Source*: OBIS/IOC-UNESCO

Conclusions and next steps

It is remarkable that about half of all catalogued marine species have been reported in MPA, considering that these occupy only 9% of the total ocean area (Figure 10). Furthermore, a significant 72% of species facing the threat of extinction find refuge within MPA and even 54% occur in the highest level of protection (also called no-take zones). However, it is important to note that only a fraction of their reported distribution falls under the highest level of protection (Figure 11), raising questions about the effectiveness of safeguarding threatened species in these areas.

That MPA have more published species distribution records than non-MPA may reflect that areas of scientific interest have been designated as MPA, and that once designated there is increased interest in understanding the biodiversity of these areas (50% of all data in MPA were collected in the past eight years). It is important to acknowledge a caveat in these statistics – the data do not provide insight into the current presence of these species in MPA, nor their abundance both inside and outside these designated areas. Nevertheless, these findings are promising, suggesting that existing MPA areas serve as a commendable starting point in the endeavour to safeguard marine biodiversity, crucial for supporting both food security and the overall health of our oceans. Establishing new MPAs and increasing their coverage have the potential of maximizing fisheries and improving the delivery of ecosystem services to the associated human communities. In addition, they show how indicators of progress in conservation can be quickly derived from data that are accessible to everyone at no cost (i.e. open access) and be reproducible. Incentivizing sharing more data to global databases such as OBIS would increase the spatial and temporal resolution of such indicators, providing more refined information to guide the management and conservation of marine ecosystems.

Acknowledgements

We are grateful to the thousands of data providers who collectively have published several 100 millions of marine species distribution data in the public domain through OBIS and GBIF. We also thank ProtectedSeas for providing us the data and shapefiles of the MPA. Both Silas Principe and Mark J. Costello received support from Horizon Europe project MPA Europe (GA 101059988).

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Additional resources

Data processing source code and download links are available at: https://github.com/iobis/protectedseas-statistics

The ProtectedSeas Navigator Map of Conservation Regulations. Available at: https://map.navigatormap.org

Marine spatial planning – A global update

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Introduction

Marine (or Maritime) spatial planning (MSP) is a key area-based policy to sustainably manage human activities within maritime territories of countries on all continents. It is a process to allocate human activities as well as priority areas for coastal and marine protection and restoration to achieve a productive, healthy, and resilient ocean.

Through the joint MSP roadmap, IOC-UNESCO is continuously working with the European Commission to promote MSP (IOC-UNESCO/European Commission, 2022). With the support of countries, collaborators and MSP practitioners, IOC-UNESCO is also tracking the status of MSP processes through its survey on MSP sent every two years to countries. In addition, status and updates are researched through complementary desk research of key sources, such as the European MSP Platform, governmental and projects' websites and publications, as well as discussions with the MSPglobal network of MSP practitioners.

Key findings, trends and status

By the end of 2023, a total of 126 countries/territories were identified as engaged in MSP initiatives – an increase of 20% from the assessment completed for the 2022 Pilot StOR (IOC-UNESCO, 2022), most notably in Africa and Oceania (Figure 12). Engagement in MSP is defined here as the existence of at least a pilot project in the country or an MSP working group established by the government to initiate discussions and scoping.

The increased number in Africa comes from projects led by international organizations and cooperation mechanisms supporting MSP in the Benguela Current, Western Mediterranean, Western Indian Ocean and part of the Gulf of Guinea (Mami Wata, 2023; MARISMA, 2023; MSPglobal, 2023a; SwAM, 2023a; TNC, 2023). These projects are mainly focused on the development of capacities and assessments relevant for the planning process. Some areas in Africa are yet to fully engage in MSP, such as Central Africa.

Initiatives in Oceania (MACBIO, 2023; Waitt Institute, 2023), the Caribbean (OECS, 2023) and Southeast Asia (COBSEA, 2023; WESTPAC, 2023) reflect similar support by international cooperation. In the continental part of the Americas, most of the countries have engaged in MSP but approved plans are mainly in North America. On the other hand, the number of countries engaged in MSP in Europe remains high and stable due to the European Union Directive on MSP, which required all its coastal countries to approve a marine spatial plan by 2021; although a few plans are yet to be adopted (EU MSP Platform, 2023).

Notably, 45 countries/territories have now approved national, subnational and/or local plans, a 10% increase on last year. This number is still low, as the development and approval of a marine spatial plan takes years due to the nature of the necessary assessments and engagement of stakeholders. It is critical to note that the transition from MSP discussions to approved plans does not happen until an authority is appointed. Besides, in countries that lack a legal framework, which can take years to be established, plans can be used as a guiding document, but this might result in implementation gaps.

MSP is widely used as a platform for multisectoral engagement and negotiation of diverse interests. A current common trend is the link between MSP and the development of sustainable ocean (or blue) economies. This is clearly exemplified by a more than 25% increase in the number of parties that have joined the High Level Panel for a Sustainable Ocean Economy[3] and their commitment to develop sustainable ocean plans, an umbrella for marine policies that includes MSP (Ocean Panel, 2023). At the same time, the MSP approach is continually promoting the achievement of significant conservation goals, such as Target 1 (on participatory, integrated and biodiversity inclusive spatial planning) and Target 3 (on at least 30% of coastal and marine areas effectively conserved and managed by 2030) of the Kunming-Montreal Global Biodiversity Framework.[4] MSP has become the focus of calls for social inclusion and social justice, especially concerning Indigenous peoples and local communities (IPLCs) as well inclusion of gender and poverty issues (MSPglobal, 2023b; SwAM, 2023b).

Finally, the development of climate-smart marine spatial plans is seen as an opportunity to integrate climate adaptation and mitigation measures towards resilient marine ecosystems and less vulnerable coastal communities and economies. However, the full integration between MSP and climate change is still limited (UNESCO-IOC, 2021) and more work is needed to

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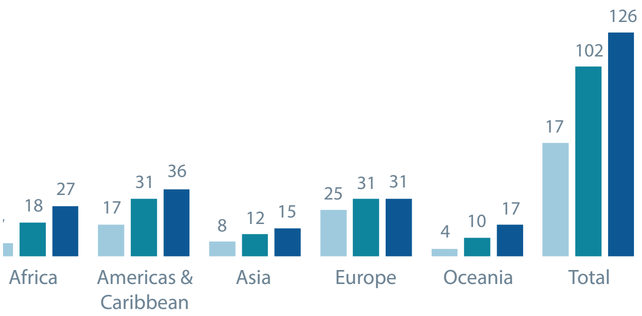
[3] See https://oceanpanel.org/.

[4] See https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf.

(A) Countries/territories engaged in marine spatial planning



(B) Countries/territories with approved marine spatial plans

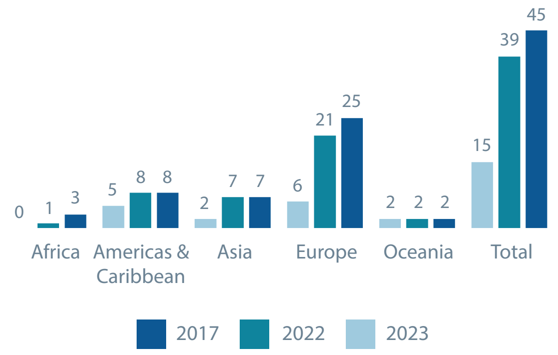


Figure 12. IOC-UNESCO assessments about Marine Spatial Planning status around the world: **a**. Number of countries/territories engaged in MSP; and **b**. Number of countries/territories with approved Marine Spatial Plans at national, subnational and/or local level. Source: IOC-UNESCO.

clarify approaches for climate-smart MSP.

MSP is a process that facilitates the adoption of a transparent, inclusive and participatory approach to multi-objective planning. In addition to planning national marine areas, there are growing interests in transboundary MSP (e.g. Baltic Sea, North Sea and Western Indian Ocean) and its application in Areas Beyond National Jurisdiction.

Conclusion and next steps

The adoption of MSP continues to accelerate worldwide, with the approval and implementation of marine spatial plans still relatively low beyond Europe, perhaps due to the lack of legal frameworks. Monitoring and evaluation of MSP around the word is important to understand how the plans are implemented and can be improved. An in-depth monitoring and evaluation needs to cover the following: (i) the process itself, including degree of stakeholder engagement; (ii) the plan and its relevance; (iii) the implementation of the plan; and (iv) the outcomes of the plan (UNESCO-IOC/European Commission, 2021). As a first step, to analyse the first two aspects, a typology of ten criteria was proposed in the 2022 Pilot StOR and presented during the 3rd International Conference on MSP. IOC-UNESCO will implement this typology for the first time in its next survey on MSP, which is scheduled for mid-2024.

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Waitt Institute. 2023. *Our Projects*. https://www.waittinstitute.org/initiatives

WESTPAC. 2023. *UN21: Accelerate Marine Spatial Planning in the Western Pacific*. https://ioc-westpac.org/decade-actions/msp/

Additional resources

Country profiles about the status of MSP around the world: https://www.mspglobal2030.org/msp-roadmap/msp-around-the-world/

Protecting coastal blue carbon ecosystems

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Introduction

Healthy marine and coastal ecosystems provide a wide array of benefits, including biodiversity and habitat support, water filtration, coastal protection from storm surges and erosion, carbon sequestration and storage, and livelihoods of coastal communities, as well as aesthetic and recreational values. According to the Intergovernmental Panel on Climate Change (IPCC), all biologically driven carbon fluxes and storage in marine systems that are amenable to management can be considered as blue carbon (IPCC, 2019). At present, this definition encompasses mangroves, tidal marshes and seagrasses, for which established methodologies for carbon accounting are available and recognized by the IPCC (IPCC, 2014). Other ecosystems, such as macroalgae, benthic sediments and mudflats, are emerging as blue carbon, but uncertainties remain as to the rates of sequestration and permanence of carbon in these habitats (Conservation International *et al.*, 2023).

Key findings, trends and status

Coastal blue carbon ecosystems sequester carbon from the atmosphere and store it in the biomass and in the sediments below for hundreds to thousands of years, if undisturbed, with the highest rates of nature-based carbon sequestration per area: 168 g C m-2 yr-1 in mangroves, 242 g C m-2 yr-1 in tidal marshes and 83 g C m-2 yr-1 in seagrasses (Conservation International *et al.*, 2023). However, when these ecosystems are degraded or lost, for example when mangroves are converted to shrimp ponds, up to 92% of their original carbon stocks, as well as other greenhouse gases such as methane and nitrous oxide, are released into the atmosphere, thus exacerbating climate change (Schindler Murray and Milligan, 2023). It is estimated that human activities such as destructive fishing practices, pollution, coastal infrastructure development and land-use change, combined with the impacts of climate change on these ecosystems, have resulted in the loss of 20–35% of their global cover since 1970 (Schindler Murray and Milligan, 2023).

At the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC COP 21) in 2015 in Paris, France, the International Partnership for Blue Carbon (IPBC) was launched under the leadership of Australia with the aim to increase global efforts to conserve, restore and sustainably manage coastal blue carbon ecosystems for climate change mitigation and adaptation, biodiversity, ocean economies and livelihoods of coastal communities. In 2023, the IPBC counts over 50 partners, including 18 countries that spearhead blue carbon action at all levels, and is coordinated by Australia with the support of the IOC/UNESCO.

Increased efforts towards the protection of coastal habitats can take several forms. For example, 62 out of 148 countries included the conservation or restoration of coastal blue carbon ecosystems as a mitigation component of their new or updated Nationally Determined Contribution (NDC) to the Paris Agreement, as of October 2023 (Lecerf *et al.*, 2023). The inclusion of coastal blue carbon ecosystems in national climate mitigation strategies goes hand in hand with their inclusion in the national greenhouse gas inventory (GHGI); however, to date only a few countries have included coastal blue carbon ecosystems in both the NDC and GHGI, while some countries may include them in the NDC only, or in the GHGI but not in the NDC (Figure 13 provides an overview for the 18 IPBC country Partners). Some countries – such as Somalia in the IPBC – may also recognize coastal wetlands for their adaptation value in their NDC, even when clear, quantifiable targets related to their climate mitigation potential are not available yet. Besides NDCs, some countries recognize the role of coastal wetlands for climate change mitigation and adaptation also in their National Biodiversity Strategies and Action Plans (NBSAPs, Figure 14).

Other international frameworks such as the Convention on Wetlands of International Importance (Ramsar Convention) and the UNESCO World Heritage Convention, also provide opportunities for countries to accelerate the protection of coastal habitats, for example, through the designation of Ramsar Sites and UNESCO World Heritage Sites in coastal areas encompassing blue carbon ecosystems, which may lay the groundwork for a better protection of these habitats (Table 1).

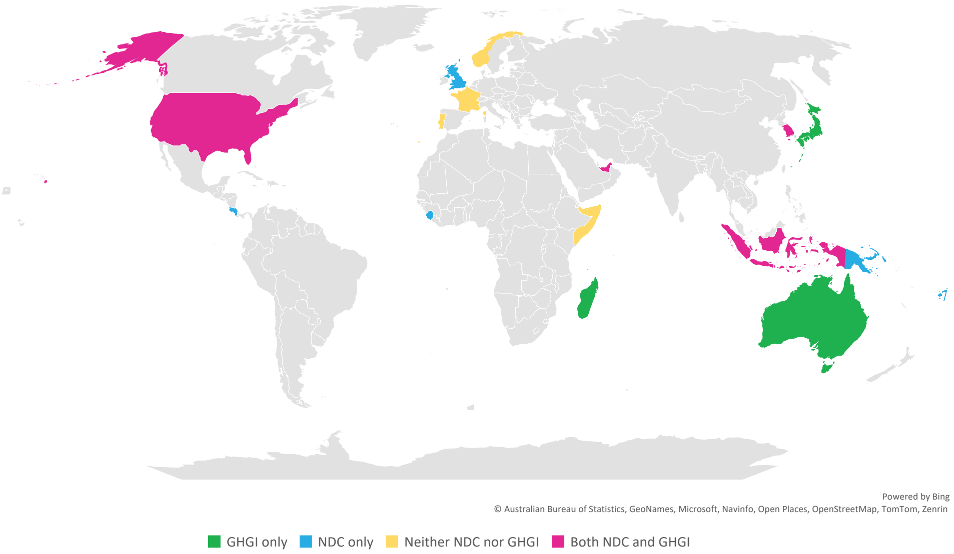

Figure 13. Status of inclusion of coastal blue carbon ecosystems for climate change mitigation in IPBC country Partners' new or updated Nationally Determined Contributions (NDC) to the Paris Agreement (as of 31 March 2024) and national greenhouse gas inventories (GHGI). Four out of 18 countries include coastal blue carbon ecosystems in both the NDC and GHGI (Indonesia, Republic of Korea, United Arab Emirates and United States of America); 6 out of 18 countries include coastal blue carbon ecosystems in the NDC only (Costa Rica, Fiji, Papua New Guinea, Seychelles, Sierra Leone and the United Kingdom of Great Britain and Northern Ireland); 3 out of 18 countries include coastal blue carbon ecosystems in the GHGI only (Australia, Japan and Madagascar); and 4 out of 18 countries include coastal blue carbon ecosystems neither in the NDC nor in the GHGI (France, Monaco, Norway and Somalia). Note: Australia, Republic of Korea and the United States of America are the only countries that include coastal blue carbon ecosystems in the GHG under wetlands. The rest of the countries include mangroves under the forest sector. Source: IPBC with data from Lecerf *et al.* (2023) and the IPBC Survey (2021, 2022 and 2024), validated by IPBC country Partners' focal points.

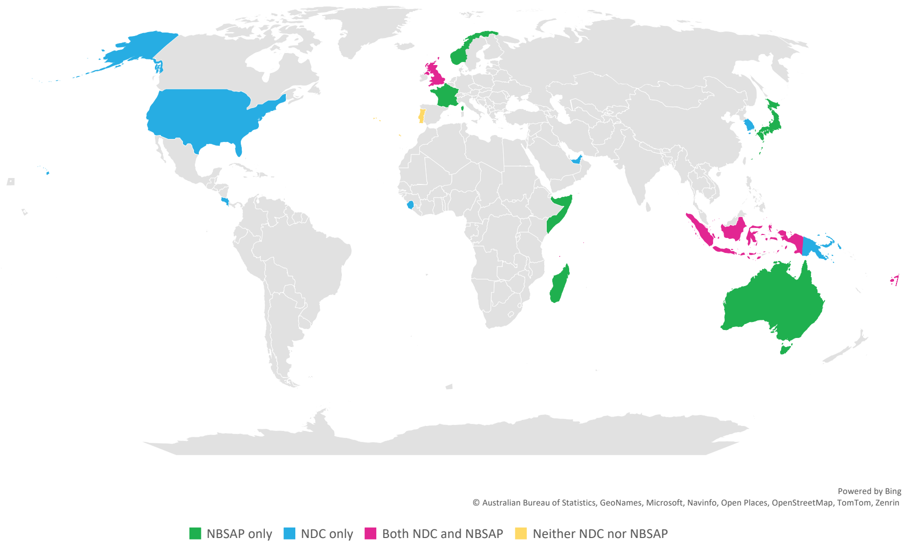

Figure 14. Status of inclusion of coastal blue carbon ecosystems for climate change mitigation in IPBC country Partners' new or updated Nationally Determined Contributions (NDC) to the Paris Agreement and new or updated National Biodiversity Strategies and Action Plans (NBSAP). Four out of 18 countries include coastal blue carbon ecosystems in both the NDC and NBSAP (Fiji, Indonesia, Seychelles and the United Kingdom of Great Britain and Northern Ireland); 6 out of 18 countries include coastal blue carbon ecosystems in the NDC only (Costa Rica, Papua New Guinea, Republic of Korea, Sierra Leone, United Arab Emirates and the United States of America); 6 out of 18 countries include coastal blue carbon ecosystems in the NBSAP only (Australia, France, Japan, Madagascar, Norway and Somalia); and 2 out of 18 countries include coastal blue carbon ecosystems neither in the NDC nor in the NBSAP (Monaco and Portugal). Note: At the time of drafting this report, no information is available about the inclusion of coastal blue carbon ecosystems in the NBSAP of the United Arab Emirates and the United States of America. Source: IPBC with data from Lecerf *et al.* (2023), the Secretariat of the Convention on Biological Diversity (CBD) (updated as of 31 March 2024) and the IPBC Survey (2021, 2022 and 2024), validated by IPBC country Partner's focal points.

Table 1. Number and total area (ha) of Ramsar Sites and UNESCO World Heritage Sites in IPBC country Partners that contain one or more coastal blue carbon ecosystems.

IPBC country Partner	Number of Ramsar Sites containing one or more coastal blue carbon ecosystems	Total area of Ramsar Sites containing one or more coastal blue carbon ecosystems (ha)	Number of UNESCO World Heritage Sites containing one or more coastal blue carbon ecosystems	Total area of UNESCO World Heritage Sites containing one or more coastal blue carbon ecosystems (ha)
Australia	27	3 623 828	6	39 138 400
Costa Rica	7	240 190	2	346 700
Fiji	1	134 900	-	-
France	17	650 401	3	70 170 100
Indonesia	5	1 292 976	2	297 847
Japan	10	27 727	1	71 100
Madagascar	6	623 569	-	-
Monaco	1	23	-	-
Norway	12	16 325	1	122 712
Papua New Guinea	1	590 000	-	-
Portugal	6	59 538	-	-
Republic of Korea	8	18 010	4	129 346
Seychelles	2	44 024	1	35 000
Sierra Leone	1	295 000	-	-
Somalia	-	-	-	-
United Arab Emirates	5	18 816	-	-
United Kingdom of Great Britain and Northern Ireland	65	455 548	2	422 101
United States of America	8	1 037 470	3	46 613 637

Source: IPBC (2024) with data from the Secretariat of the Convention on Wetlands and the UNESCO World Heritage Centre (2020) (updated as of 31 March 2024), validated by IPBC country Partners' focal points.

Conclusions and next steps

Strengthening and aligning commitments across relevant international policy frameworks is one of the possible ways for countries to increase their efforts towards a better protection of coastal blue carbon ecosystems (IUCN and Conservation International, 2023). Progressively integrating coastal wetlands into national climate and biodiversity strategies, while at the same time reinforcing existing protection mechanisms provided by multilateral treaties such as the Ramsar Convention and the UNESCO World Heritage Convention allows countries to streamline national action on blue carbon. The global stocktake process, the next round of NDCs due in 2025 and the new Kunming-Montreal Global Biodiversity Framework (GBF) all provide an opportunity for countries to enhance their current ambition, and international networks such as the IPBC and the Blue Carbon Initiative (BCI) offer a space for governments, scientists and practitioners to exchange knowledge and learn from each other's experiences to collectively drive global blue carbon action forward.

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A productive ocean supporting sustainable food supply and a sustainable ocean economy

The contribution of aquatic foods to food security and nutrition

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[1] Food and Agriculture Organization of the United Nations

Introduction

The world will have an additional 2 billion people to feed in the next 25 years. Aquatic foods are already making a significant contribution to food security, nutrition and healthy diets, as the per capita consumption of aquatic foods over the last decade has grown at twice the rate of population growth (FAO, 2022; UN Nutrition, 2021). They are also drivers of employment, economic growth, social development and environmental recovery, while also providing essential nutrients for healthy diets, and they hold the potential to play an even bigger role in the future global food system.

The Decade for Ocean Science for Sustainable Development envisions a productive ocean that supports sustainable food supply and a sustainable ocean economy (Challenge 3 – Sustainably feed the global population). By applying scientific knowledge toward innovative solutions and to inform sound decision-making, we can optimize the role of aquatic foods in sustainably feeding the world's population under changing environmental, social and climate conditions, achieving a productive ocean capable of supporting sustainable food supply and a sustainable ocean economy.

Status and trends in fisheries and aquaculture

Fisheries and aquaculture production continues to grow, reaching a record of 218 million tonnes in 2021. This includes 182 million tonnes of aquatic animals[5] (Figure 15) and an additional 36 million tonnes of algae. This production takes place both in marine and inland waters; while 88% of capture fisheries come from marine waters, almost 62% of aquaculture takes place inland (algae excluded, Figure 15, Table 2). It is important to reflect that while capture fisheries have remained largely stable since the mid-1990s (92.1±2.25 Mt), aquaculture has been growing at a rate of 5.2% per year in the same period.

Not all this production is used for direct human consumption. Approximately 20 million tonnes of marine capture fisheries (average 2010–2021) are used for animal feed, particularly aquaculture, but also pig and poultry farming, as well as nutritional supplements and other non-food uses. Despite some natural variability in the resource base, this volume has in fact been declining from a record 34 million tonnes in 1994 (Figure 16).

According to FAO's latest information, if considering only aquatic animals, in 2021 aquatic food production reached a record 161 million tonnes, of which 94 million tonnes are from capture fisheries and aquaculture in marine areas (Table 2). This production translates into an apparent per capita consumption of aquatic foods of 20.4 kg/yr in 2021 (Figure 16), more than double the per capita consumption rate in 1960.

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[5] Aquatic animals include fish, crustaceans, molluscs and other aquatic animals, excluding aquatic mammals, crocodiles, alligators, caimans, algae and other aquatic animal products (corals, sponges, pearls).

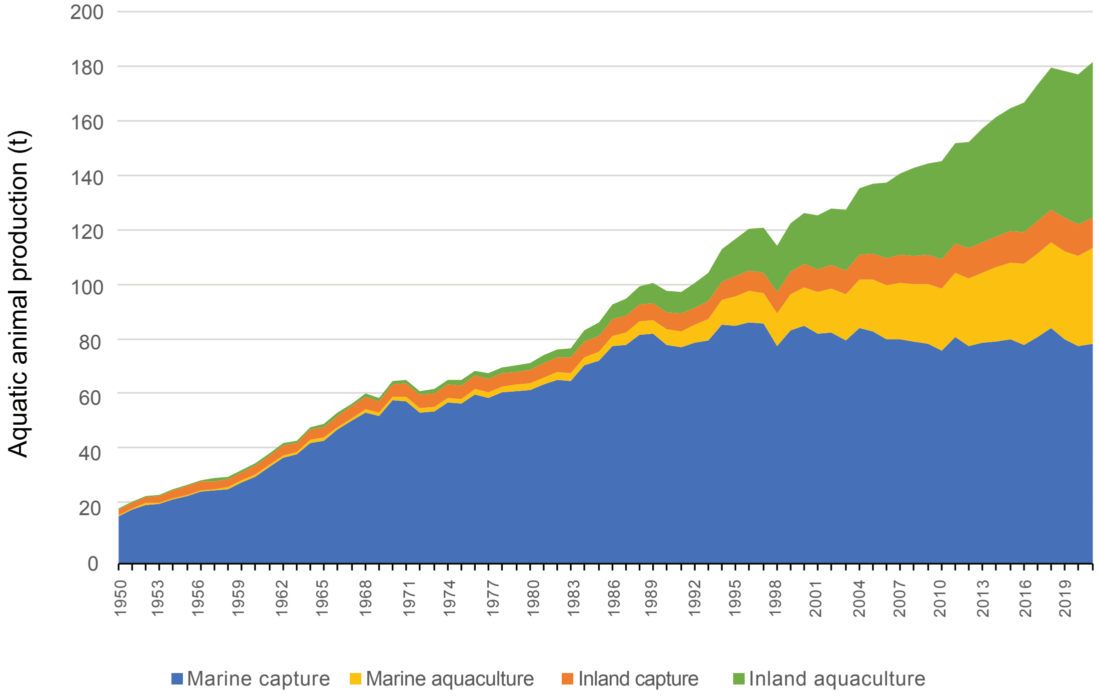

Figure 15. World fisheries and aquaculture production of aquatic animals 1950–2021, by production sub-sector. Source: FAO, 2024.

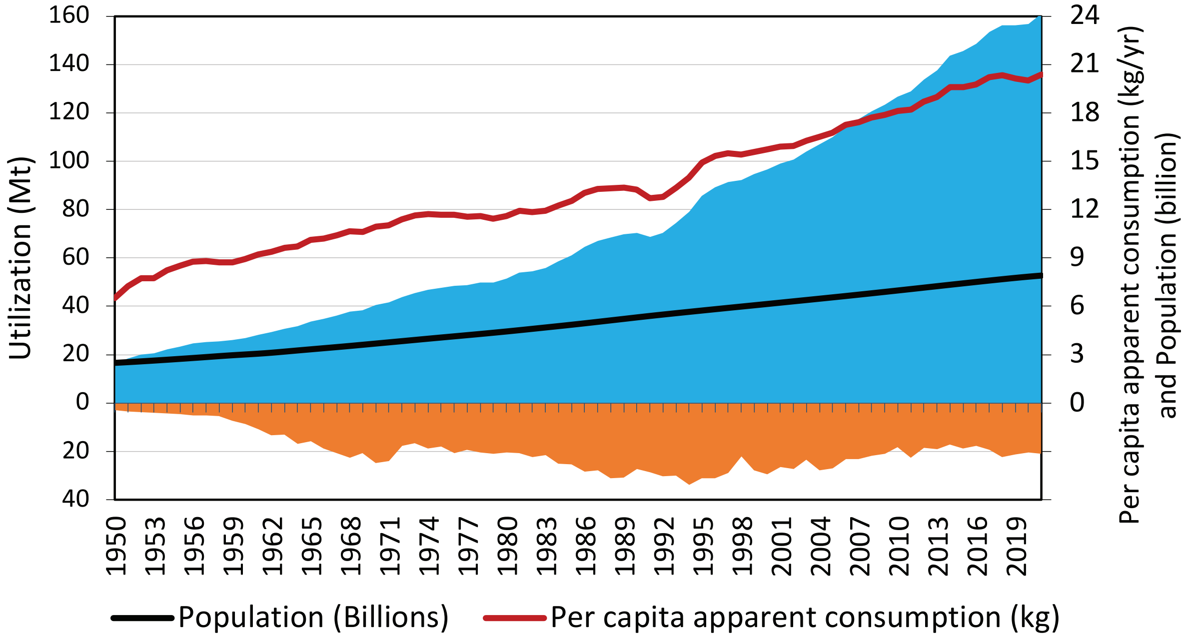

Figure 16. World fisheries and aquaculture production of aquatic animals: utilization and apparent consumption. Source: Updated from FAO, 2022.

Table 2. World production of aquatic animals in 2021 in million tonnes (FAO, 2024). Note that not all marine capture fisheries production is used for direct human food (see text)

Production	Inland waters	Marine areas	Total
Capture fisheries	11.4	79.8	91.2
Aquaculture	56.2	34.6	90.9
Total	67.6	114.5	182.1

Aquatic food			
Capture fisheries	11.4	58.8	70.3
Aquaculture	56.2	34.6	90.9
Total	67.6	93.6	161.1

Source: FAO, 2024.

Despite this, it is surprising how aquatic foods have been undervalued as a nutritional solution, partially because they are often reduced to their protein contribution. This perception is changing, as the diversity of aquatic foods (approximately 3,400 taxa harvested and 700 species or species-types cultured, (FAO, 2024)) and their unique contribution in the form of bioavailable micronutrients and long-chained polyunsaturated omega-3 fatty acids is increasingly recognized. As a result, their potential to address the 'triple burden of malnutrition' (micronutrient deficiencies, undernutrition, and overweight and obesity) is growing (UN Nutrition, 2021). The consumption of aquatic foods is particularly effective in addressing deficiencies among vulnerable demographic groups, such as young children and older people, and women of childbearing age.

An added focus on aquatic foods comes from the reality of needing to feed a growing population in the era of climate change. Looking for efficient and impactful food solutions is paramount. An advantage that aquatic foods provide is that many of their production systems have lower environmental footprints compared to terrestrial animal-source food systems (MacLeod *et al.*, 2020), in particular unfed aquaculture systems such as bivalves and seaweeds. On average, aquatic food production also results in low greenhouse gas (GHG), nitrogen and phosphorus emissions, and requires limited (or no) freshwater and land inputs. They are also more efficient in converting feed to flesh than land-based animals (Fry *et al.*, 2018). In summary, aquatic foods are more efficient and sustainable than land-based animal food production systems and have a potential to be more impactful through technological innovation. Considering the pressures on land-based food production systems, ending hunger and malnutrition without aquatic foods seems difficult. In fact, in the build-up to the 2021 UN Food Systems Summit, sustainable aquatic foods were identified as one of the top priorities to end hunger and protect the planet (Von Braun *et al.*, 2021).

While the focus of this summary is on global trends, challenges and opportunities, aquatic foods are not equally important everywhere. Many Small Island Development States (SIDS), including Maldives, Kiribati, Antigua and Barbuda, have consumption rates of aquatic foods significantly above the global average, demonstrating high dependence on the sector (FAO, 2024). As stated in the SIDS Accelerated Modalities of Action (SAMOA) Pathway (UN General Assembly, 2014) sustainable fisheries and aquaculture are among the main building blocks of a sustainable ocean-based economy in SIDS.

Furthermore, in many Low Income Food Deficit Countries (LIFDC) small-scale fisheries are the main producer of aquatic foods, estimated to account for 40% of the global fisheries catch and supporting *the livelihoods of about 500 million people globally (FAO, WorldFish and Duke University, 2023). Almost half of those fishers operate in subsistence fisheries, demonstrating the crucial safety net that the sector provides to many, and the importance of equitable access rights as promoted by the FAO Voluntary Guidelines for Securing Sustainable Small Scale Fisheries in the Context of Food Security and Poverty Alleviation (FAO, 2015) in the conversation over aquatic foods.*

Conclusions and next steps

The production and processing of aquatic foods are very diverse, with equally diverse consumption patterns, nutrient profiles, and environmental, social and economic impacts. To achieve future expectations, aquatic foods need to be made more sustainable and impactful, starting with capture fisheries. Although over 80% of the marine fisheries landings of stocks monitored by FAO (by volume) are from sustainably exploited stocks, over 35% of these commercial stocks (by number) are unsustainably exploited (FAO, 2022). Rebuilding fish stocks could increase the contribution of marine fisheries to food security and nutrition. Aquaculture practices vary as well, and the recent development of FAO Guidelines of Sustainable Aquaculture (GSA) provides guidance to ensure aquaculture practices continue to reduce their environmental footprint and impacts (FAO, 2023).

Thus, in conclusion, a deeper appreciation and understanding of the role that aquatic foods can play is essential to harness their unique capacity for addressing nutritional, social and environmental food system challenges. The FAO has developed a Blue Transformation roadmap, providing an objective-driven strategy for governments, intergovernmental organizations, the private sector and civil society to ensure aquatic foods provide more solutions to today's problems. It aims at growing aquaculture sustainably, especially in food deficit regions; ensuring all capture fisheries are placed under effective management because management works; and developing the value chains of aquatic foods, reducing loss and waste, adding value to products and facilitating their access to markets, especially for small producers. Through a Blue Transformation, we will ensure aquatic foods increase their contribution to feed a growing population with nourishing foods in the context of a changing climate.

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A predicted ocean where society understands and can respond to changing ocean conditions

Assessing ocean prediction capabilities for sustainable development

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Introduction

Ocean predictions are integral to advancing numerous Sustainable Development Goals (SDGs), notably those concerning marine life, ecosystems, climate action and sustainable resource management. This brief paper will provide an overview of the current state of knowledge and analysis, reanalysis and forecasting systems developed.

The development of ocean forecasting began in the early 1980s (Pinardi *et al.*, 2017), with operational services being implemented in the early 2000s (Alvarez Fanjul *et al.*, 2022). Today, global, regional and coastal operational prediction systems have matured to a large extent to provide actionable use cases. Ciliberti *et al.* (2023) offer the most recent assessment of user satisfaction regarding operational products at the global, regional and coastal levels.

Figure 17 illustrates the progression of the Mercator Ocean International (MOI) global operational system in action (Lellouche *et al.*, 2018; 2023), highlighting the advancements in error reduction compared to altimetric observations over recent years.

Regional and coastal operational systems have also advanced, covering additional challenges and needs that demand the solution of complex physical phenomena at higher spatial and temporal resolution. To attain the higher resolution required for coastal applications, limited area numerical models are employed (Federico *et al.*, 2017; Trotta *et al.*, 2021; García-León *et al.*, 2022, etc.). These models necessitate consistent and frequent coastal observations for validation, calibration and data assimilation, along with comprehensive large-scale ocean analyses and predictions, to supply initial and lateral boundary conditions. Figure 18 illustrates an instance of enhanced precision achieved by incorporating a shelf and coastal model within a larger regional model. Recently and increasingly, machine learning algorithms have been utilized for downscaling, especially in storm surge forecasting (Qin *et al.*, 2023).

As an example of the complex phenomena to be solved, and the need for seamless forecasting from the deep ocean to the coastal regions, fluctuations in offshore density currents have a notable effect on coastal sea levels (Dangendorf *et al.*, 2021). Therefore, the precision of coastal forecasts relies on both the domain size and the quality of the large-scale flow field utilized for nesting.

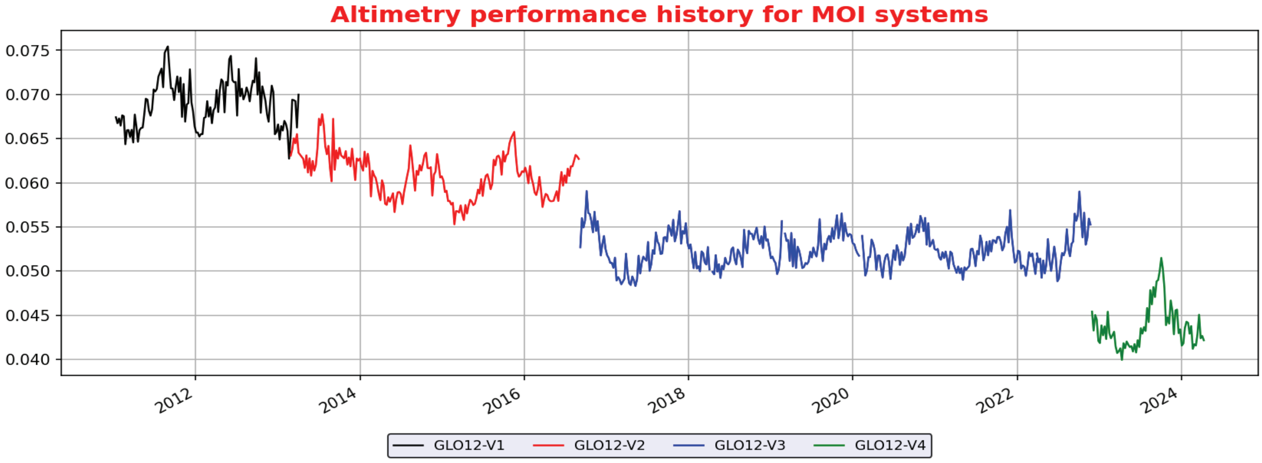
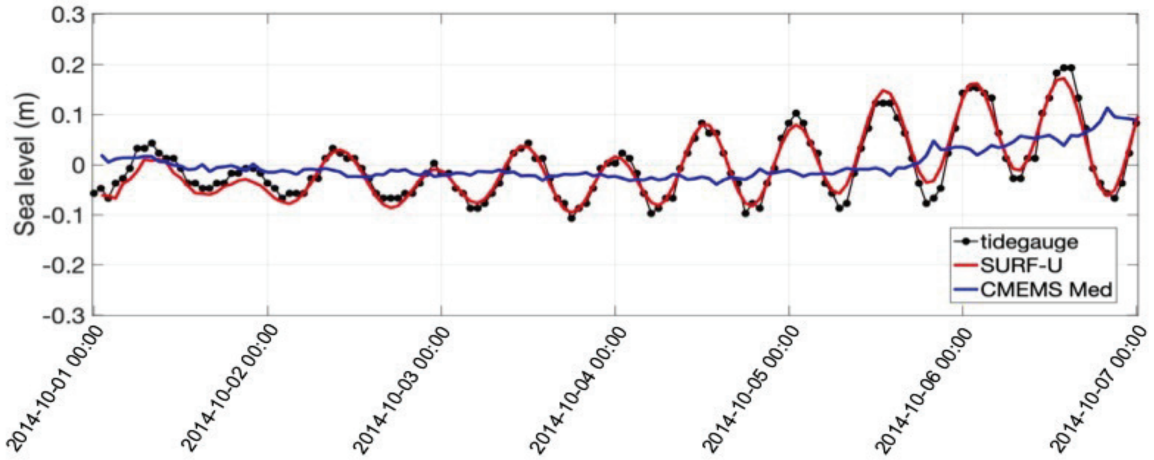


Figure 17. Evolution in time of the sea level error of the Global Copernicus Marine Ocean forecasting service. Four versions of the system have been operated since 2011, with the green curve showing the current system in operation since the end of 2022.
Notes: GLO12-V1 (black curve) version of the MOI global analysis and forecast system from 2011–2012; GLO12-V2 version of the system from 2013–2016; GLO12-V3 version of the system from 2017–2022; GLO12-V4 version of the system from 2022 to today).

Source : MOI-Mercator Ocean International ; Lellouche *et al.*, 2018 ; 2023).



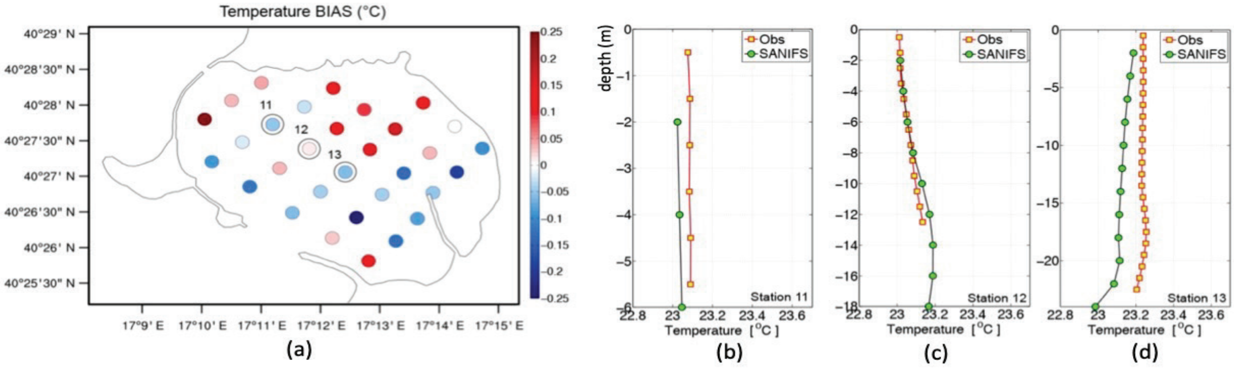


Figure 18. Upper Panel: sea level at a coastal tide gauge station inside the Port of Taranto; red line is the coastal model, black dots are the tide gauge observations and the blue line is the large-scale regional model. Lower Panel: (a) CTD stations in the Gulf of Taranto; (b,c,d) comparison between coastal model (green profiles) and observed profiles (orange profiles) at three stations listed with numbers 11, 12 and 13 in (a). *Source*: adapated from Federico *et al.* (2017)

For instance, hurricanes along the United States East coast can shift the Gulf Stream's position (Kourafalou *et al.*, 2016), transmitting mixed baroclinic/barotropic signals to the shelf and amplifying storm surges (Park *et al.*, 2021).

Key findings, trends and status

Table 3, extracted from Alvarez Fanjul *et al.* (2022) provides an overview of the capacity of global and regional ocean analysis, reanalysis and forecasting systems. For comprehensive insights into the numerical resolution and data assimilation components of each system, it is advised to consult this publication.

While the number of systems continues to increase, there remains a significant imbalance between those in the northern and southern hemispheres, spanning global, regional and coastal areas. This disparity primarily stems from the need for extensive supercomputing infrastructure. However, recent advancements, such as the development of the first global ocean eddy-resolving forecasting system using Artificial Intelligence (AI) models (Wang *et al.*, 2024), offer promise for reducing this gap. With these data-driven systems, a 10-day forecast can be computed in less than a minute.

An urgent area requiring attention is the enhancement of global, regional and coastal forecasting capabilities for biogeochemistry. While many systems outlined in Table 1 incorporate both physics and biogeochemistry in their analysis, reanalysis and forecasting, the lack of sufficient real-time biogeochemical observations, such as Bio-ARGO and coastal monitoring stations is hindering the swift progress of this aspect. Prominent instances include the Copernicus Marine Service (as discussed by Le Traon *et al.*, 2019) and the work by Siedlecki *et al.* (2016) focusing on the North-Western Pacific and seasonal temporal scales.

Ocean forecasting's best practices consider standards across the ocean value chain (Pinardi *et al.*, 2019), spanning observation to service delivery. Historically, guides tackled Essential Ocean Variables (EOVs) separately, like WMO Guides (2018; 2022) for waves and coastal inundation. The recent guide, Implementing Operational Ocean Monitoring and Forecasting Systems (Alvarez Fanjul *et al.*, 2022) addresses components and standards of multihazard, multisectoral operational forecasting systems listed in Table 3. The guide offers an updated table of operational systems up to 2022 showing the many systems, but a limited account for other systems that have been developed in the last two years.

Table 3. List of operational forecasting and multi-year reanalysis systems

No.	Inventory of operational forecasting systems	Region of application
1	OceanMAPS, BLUElink (Bureau of Meteorology)	Global ocean
2	Global Ice Ocean Prediction System (Government of Canada)	Global ocean
3	ECCO reanalysis (JPL, USA)	Global ocean
4	FOAM analysis and forecasting systems (MetOffice, UK)	Global ocean
5	NAVOCEANO analysis and forecasting system (US Naval Oceanographic Office, USA)	Global ocean
6	INCOIS analysis and forecasting system (Indian National Centre for Ocean Information Service, India)	Global ocean
7	GOFS16 Forecasting System (CMCC, Italy)	Global ocean
8	Global forecast and reanalysis system by Copernicus Marine Service (MOI, France)	Global ocean
9	MOVE/MRI.COM- JPN (MRI, Japan)	Global, North Pacific, Japan seas
10	Arctic forecasting and reanalysis system by Copernicus Marine Service (NERSC, Norway)	Arctic Region
11	Baltic forecasting and reanalysis system by Copernicus Marine Service (SHMI, Sweden)	Baltic Sea
12	Mediterranean Sea forecasting and reanalysis system by Copernicus Marine Service (CMCC, Italy)	Mediterranean Sea
13	Irish-Biscay-Iberian shelves forecasting and reanalysis system by Copernicus Marine Service (MOI, France / Spain)	Irish-Biscay-Iberian shelves
14	North-West shelf forecasting and reanalysis system by Copernicus Marine Service (Met Office, UK)	North-West shelf
15	Black Sea forecasting and reanalysis system by Copernicus Marine Service (CMCC, Italy)	Black Sea
16	High Resolution Data Assimilative Model for Coastal and Shelf Seas around China (Institute of Atmospheric Physics/Chinese Academy of Sciences, China)	Northwest Pacific, coastal seas around China
17	MARC: Modelling and Analyses for Coastal Research and ILICO: Coastal Ocean and Nearshore Observation Research Infrastructure (Ifremer, France)	Bay of Biscay/English Channel/Northwestern Mediterranean Sea
18	SOMISANA (SAE- ON/DFFE, South Africa)	Algoa Bay, south coast, South Africa
19	CNAPS Coupled Northwest Atlantic Prediction System (North Carolina State University, USA)	Northwest Atlantic coast ocean, including the entire east coast of USA, the Gulf of Mexico and Caribbean seas
20	EMO Oceano- graphic Modeling and Observation Network (Brazilian Navy Hydrographic Center, Brazil)	Region between latitudes 35.5° S and 7° N and longitude 20° W to the Brazilian coast
21	DREAMS: Data assimilation Research of the East Asian Marine System (RIAM, Kyushu University, Japan)	Northwestern Pacific with focus on marginal seas
22	BSH Operational Model System (BSH, Germany)	North and Baltic Sea, German coastal waters
23	COSYNA (HEREON, Germany)	North Sea, German Bight, German Wadden Sea
24	PCOMS (MARETEC, Portugal)	Western Iberia region and subregions
25	SANIFS (CMCC, Italy)	Southern Adriatic Northern Ionian coastal Forecasting System
26	SAMOA (Puertos del Estado, Spain)	Spanish coastal and harbour domains
27	NYHOPS: New York Harbor Observation and Prediction System (Jupiter Intelligence, USA)	New York and US East Coast
28	SWITCH – Georgia Coasts (CMCC/GeorgiaTech, Italy /USA)	Georgia coast, USA
29	Tagus Mouth operational model (MARETEC/IST, Portugal)	Tagus Estuary, Portugal
30	CFSR reanalysis (Climate Prediction Center, NOAA, USA)	Global ocean
31	C-GLORS reanalysis (CMCC, Italy)	Global ocean
32	GECCO reanalysis (University of Hamburg , Germany)	Global ocean
33	ECDA reanalysis (Geophysical Fluid Dynamics Laboratory, USA)	Global ocean
34	GloSea5 reanalysis (UK MetOffice, UK)	Global ocean
35	K7-ODA reanalysis (JAMSTEC, Japan)	Global ocean
36	PEODAS reanalysis (Bureau of Meteorology, Australia)	Global ocean
37	ORAS5 reanalysis (ECMWF, UK)	Global ocean
38	MOVE-C RA reanalysis (Japan Meteorological Agency, Japan)	Global ocean
39	SODA reanalysis (NCAR, USA)	Global ocean

Source : Alvarez Fanjul *et al.* (2022). More details are available from this publication, such as the linking web sites, the model resolution and the specific data assimilation system.

Best practices for boosting capacity in ocean predictions are covered in selected online courses available through the Ocean Teacher Global Academy (OTGA[6]). Furthermore, several systems listed in Table 3 also provide such guidance. These practices primarily emphasize the effective utilization of available open-access prediction and analysis products from forecasting systems.

Moreover, there are burgeoning efforts focused on creating on-demand prediction and analysis tools available through cloud platforms. In a landmark paper, Gentemann *et al.* (2021) delineate the transformative shift in scientific and operational research practices poised to occur with the adoption of novel cloud-based information technologies.

Ocean predictions at the service of Sustainable Development Goals (SDGs).

A way to demonstrate the importance of the listed services is to describe their use to address SDGs. This section briefly describes these applications. There are many ways in which ocean predictions and their impacts are tied to the achievement of specific SDG targets. Enhancements in analysis/reanalysis and forecasting of the marine environment have widespread implications across nearly all SDGs. However, in this context, we focus on delineating the specific SDGs that exhibit the closest interconnections.

1. **SDG 14: Life Below Water – Conserve and sustainably use the oceans, seas, and marine resources for sustainable development:**

   Accurate predictions of ocean conditions, including sea waves, sea surface temperatures, currents, nutrient levels and primary producer biomass, contribute to effective marine offshore and coastal resource management. This includes fisheries management, which helps prevent overfishing and supports the sustainable use of marine resources. The OECD Report on Economics of Adapting Fisheries to Climate Change (2011) demonstrates that incorporating multiple interacting factors, including temperature stresses, storm damage, etc., allows for resilient fishery management.

2. **SDG 13: Climate Action – Take urgent action to combat climate change and its impacts:**

   Oceans play a critical role in regulating the Earth's climate. Predictions of ocean conditions are essential for understanding and modelling climate patterns, such as El Niño and La Niña events, and storm surge extremes. The integration of ocean predictions into early warning systems, climate trend assessments and risk management strategies is vital for fostering climate-resilient societies and ecosystems. Policy-makers rely on this information to develop strategies that range from addressing immediate threats to formulating sustainable, long-term climate change mitigation and adaptation plans. Enhancing coastal resilience against climate hazards relies on the advancement of coastal predictions through refining high-fidelity models and implementing digital twin technologies, as emphasized in the 2023 report from the National Academies of Sciences, Engineering and Medicine.

3. **SDG 12: Responsible Consumption and Production – Ensure sustainable consumption and production patterns:**

   Accurate predictions of ocean conditions help in sustainable fisheries management, preventing the depletion of fish stocks. Ocean and coastal predictions, as well as long time series reanalyses, can support mariculture, predicting adverse environmental effects and supporting advanced management (OECD, 2011).

4. **SDG 6: Clean Water and Sanitation – Ensure availability and sustainable management of water and sanitation for all:**

   Ocean predictions play a crucial role in understanding and controlling the dispersal of pollutants, debris and hazardous substances within the marine environment. These factors have the potential to impact land water resources. Advanced coastal predictions can simulate salt intrusions in rivers, which may influence underground water and clean water aquifers. One application of coastal ocean forecasting to water management is connected to salt intrusion predictions, integrating river and shelf zone water modelling (Maicu *et al.*, 2021; Bonamano *et al.*, 2024)

5. **SDG 7: Affordable and Clean Energy – Ensure access to affordable, reliable, sustainable, and modern energy for all:**

   Ocean predictions contribute to the understanding of ocean energy resources, such as tidal, ocean currents, thermal vertical gradient and wave energy. Ocean predictions can help assess the negative impacts of offshore wind farming on the marine ecosystem and prevent long-term impacts. In other words, accurate predictions of ocean conditions are essential for the development and deployment of clean and sustainable ocean energy technologies. Operational oceanographic products, including

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[6] See https://classroom.oceanteacher.org/.

analyses, reanalyses and digital twin modelling tools, could aid in assessing the marine environmental impact of ocean energy converters, encompassing waves, tides and offshore winds (Copping *et al.*, 2014).

6. **SDG 11: Make cities and human settlements inclusive, safe, resilient and sustainable**

   Ocean forecasting plays a vital role in advancing the sustainability of coastal cities by supporting coastal urban resilience, integrated land and marine water quality management, sustainable coastal development, blue economy initiatives and climate change adaptation efforts. An illustration demonstrating the positive outcomes of sea level predictions in safeguarding coastal cities is the MoSE flood barrier (Experimental Electromechanical Module[7]), which was constructed to protect Venice from inundation. This structure relies on sea level forecasts provided 2–3 days in advance to prepare and activate the barriers efficiently.

   Notably, the products stemming from operational oceanographic services were evaluated by a Sea Basin Checkpoint system that was established to assess the observation and forecasting/analysis capacity in Europe for several of the SDG targets (Martín Míguez *et al.*, 2019). The results showed a partial capacity and highlighted the necessity to improve the accessibility and usability of the products for several SDGs.

Conclusions and next steps

While significant advances have been made in ocean forecasting over the past decades (Figures 17 and 18), certain technical and governance challenges continue to hinder the widespread availability and effectiveness of forecasting systems and their applications for SDGs. Notably, there is a pronounced geographical imbalance, with some regions benefitting from sophisticated coastal applications, while others face a scarcity of such resources.

Furthermore, the accessibility and usability of large-scale and regional forecasts remain limited due to technological barriers associated with the exchange of large data sets and the intrinsic difficulties of the problem. The Sea Basin Checkpoint service (Martín Miguez *et al.*, 2019) conducted a thorough analysis of data availability, revealing shortcomings in the delivery mechanisms and cataloguing principles of numerous datasets.

In addressing scientific and technological challenges, it is important to note the significant difficulty in resolving both global and sub-mesoscale features. However, resolution is essential for practical applications such as search and rescue operations and forecasting marine pollutant transport. Equally complex are the required coupled land-hydrology-ocean-atmosphere predictions that are vital for coastal applications such as pollution assessment, storm surges and ecosystem health. Fully coupling numerical earth system modelling has the potential to expand the predictability limits of crucial ocean variables, despite the absence of demonstrated effectiveness in this method for the oceanic synoptic scales. On the contrary, the recent AI-based forecasts enlarge the limits of predictability up to 60 days (Wang *et al.*, 2024).

Effectively addressing this multiscale and multidiscipline challenge is at the cutting edge of our current technological capabilities. Additionally, the absence of sufficient ocean observations hinders our capacity to implement and operate accurate cost-effective forecasting services, including those based on AI techniques.

The UN Ocean Decade is an important opportunity to implement transformative changes in ocean forecasting. Collaborative structures within the Decade, such as the Ocean Observing Decade Coordination office (DCO), the OceanPrediction Decade Collaborative Center (DCC), the Data Sharing DCO and the Coastal Resilience DCC, are actively engaged with key programmes including Foresea, CoastPredict, DITTO, Ocean Observing Co-design and Ocean Best Practices. Together, they aim to develop a new framework for ocean forecasting and community knowledge that mitigates existing limitations and capitalizes on available opportunities, notably leveraging the advent of AI. It is expected that AI will substitute numerical model ocean predictions in the next 5–10 years if satellite and *in situ* observations continue to increase, especially in coastal areas.

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Sea level rise

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Introduction

Sea level continued to rise in 2023 (Figure 19). The global mean sea level is estimated by high-precision satellite altimetry from the beginning of 1993 to the end of 2023 and the linear rate over this 31-year time span is 3.4 +/- 0.3 mm/yr (e.g. Guérou *et al.*, 2023).

The global mean sea level (note that the seasonal cycle has been removed) displays interannual oscillations that are mostly due to El Niño/La Niña events. These relatively short period oscillations of a few mm amplitude result from exchange of water between the continents and the ocean. During an El Niño, the rainfall deficit over the land (in particular over the Amazon basin) is balanced by excess rainfall over the tropical Pacific ocean, leading to sea level rise. The opposite occurs during La Niña. This is particularly visible during the 2011–2012 La Niña, which led to a temporary sea level drop of several mm. On the other hand, the 2023 El Niño has not produced any significant anomaly in the global mean sea level, but other analyses (e.g. Thompson *et al.*, 2024) show a somewhat larger anomaly associated with the most recent El Niño event.

Findings: Status and trends

The analysis shown in Figure 19 also results in an acceleration estimate of 0.12 +/– 0.05 mm/yr^2 during 1993–2023 (Guerou *et al.*, 2023). Recent studies have shown that this acceleration is mostly due to accelerated ice mass loss from the Greenland and West Antarctica ice sheets, and to a lesser degree from accelerated ocean warming (e.g. Nerem *et al.*, 2018; IPCC, 2021; Cazenave and Moreira, 2022). The acceleration estimate given here is somewhat larger than those given by Nerem *et al.* (2018) and in another recent estimate by Thompson *et al.* (2024) that use a different version of the altimetry data, but the differences between those estimates and the estimate given here is not statistically significant, meaning that the conclusion that the global sea level rise rate is accelerating is robust.

The regional trend patterns in sea level show very little change from one year to another. These trends are shown in Figure 20 for the period January 1993 to June 2023. The yellow/orange colours highlight regions where the regional rate of sea level change exceeds the global mean rise. These include the Indian Ocean, the western tropical, south and north Pacific, and the south Atlantic. Regional sea level trends continue to be dominated by regional variations in ocean heat content (Hamlington *et al.*, 2020; Cazenave and Moreira, 2022). In some regions such as the Arctic, however, salinity changes due to freshwater input from the melting of sea and land ice play an important role. Contributions from the 'ice melt fingerprints' are theoretically predicted, but are not yet clearly visible, except perhaps south of Greenland in the north Atlantic (Coulson *et al.*, 2022).

Recent studies dedicated to assessing closure of the global mean sea level budget, based on Argo and GRACE space gravimetry data to estimate the steric and ocean mass contributions, indicate that for the global mean the sea level budget of the last ~20 years is nearly closed within the data uncertainties (e.g. Horwath *et al.*, 2021; Barnoud *et al.*, 2023; Thompson *et al.*, 2024).

At the coast, satellite altimetry performs poorly because of perturbing reflections from land in the altimetry radar echo. Recent reprocessing of the Jason-1, Jason-2 and Jason-3 altimetry missions for the last two decades, however, provides reliable sea level data in the world's coastal zones (e.g. Cazenave *et al.*, 2022). This new dataset shows that at a few sites the rate of sea level rise at the coast may significantly differ from that of the adjacent open ocean, but in the majority of cases the coastal and offshore sea level rise rates are similar. This suggests that coastal processes (e.g. shelf currents, trends in waves, freshwater input to estuaries, etc.) do not produce significant long-term trends.

At the same time, though, coastal sea level change as measured by tide gauges is an important complement to coastal altimetry because the tide gauges measure sea level relative to the adjacent land and, unlike satellite altimetry, include the effect of vertical land motions. This means that these measurements are the most appropriate for assessing coastal flooding risks at the local level. Vertical land motions occur at the regional scale due to post-glacial rebound (PGR), but can also change at local to hyperlocal scales due to ground water pumping or hydrocarbon extraction. As an example of the latter, a recent paper by Ohenhen *et al.* (2024) used INSAR measurements along the US east coast that are corrected for the PGR signals to show that the subsidence signals are concentrated in the urban areas, presumably due to groundwater pumping. This is important for two reasons. First, in areas affected by PGR it is expected that the tide gauges will underestimate the global sea level rise signal. Second, in areas affected by groundwater or hydrocarbon extraction, it is likely that the tide gauges will overestimate the global sea level rise signal. Either is a problem, since the global tide gauge network is still our best estimate of the stability of the satellite altimeters and hence our confidence in the altimeter-based estimated of the global ocean volume change.

Conclusions and next steps

The challenge in the coming years is to improve the space-based and in situ observing systems for monitoring sea level rise at global, regional and coastal scales. The continuation of high-precision altimetry missions, sustained measurements from Argo (including the new Deep Argo programme to sample the deep ocean) and from GRACE-type missions are fundamental. For coastal sea level, there is also a need to maintain the global in situ sea level observing system overseen by the GLOSS programme, which includes a plan for increased GNSS observations at the tide gauge sites to estimate land motion. These data will provide measurements that are complementary to those made by advanced altimeter systems, such as the recently launched SWOT mission that is already demonstrating a spectacular increase in sea level measurement resolution as compared to conventional nadir altimetry. Quantitative understanding of the physical mechanisms causing sea level changes along the world's coastlines is a major challenge that needs to be addressed. 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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[8] See https://www.aviso.altimetry.fr.

[9] See https://www.climate.copernicus.eu.

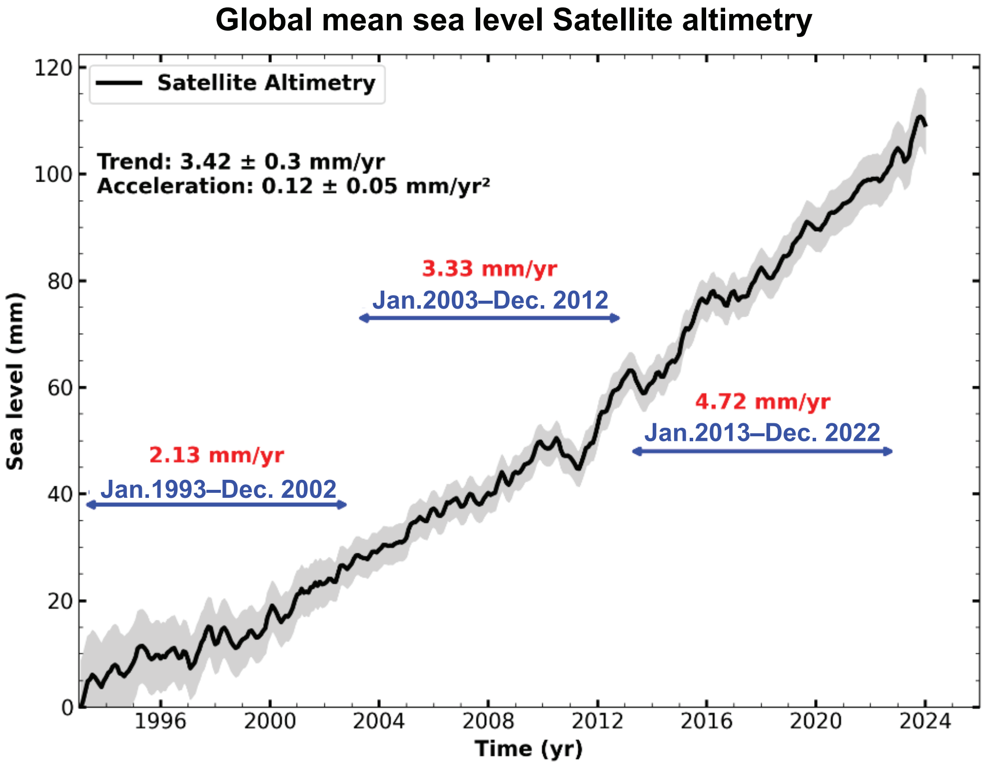

Figure 19. Global mean sea level rise from satellite altimetry from January 1993 to December 2023 (black curve). The shaded area represents the uncertainty. The blue horizontal lines indicate successive global mean sea level trends. Altimetry data from AVISO[8]. *Source*: LEGOS.

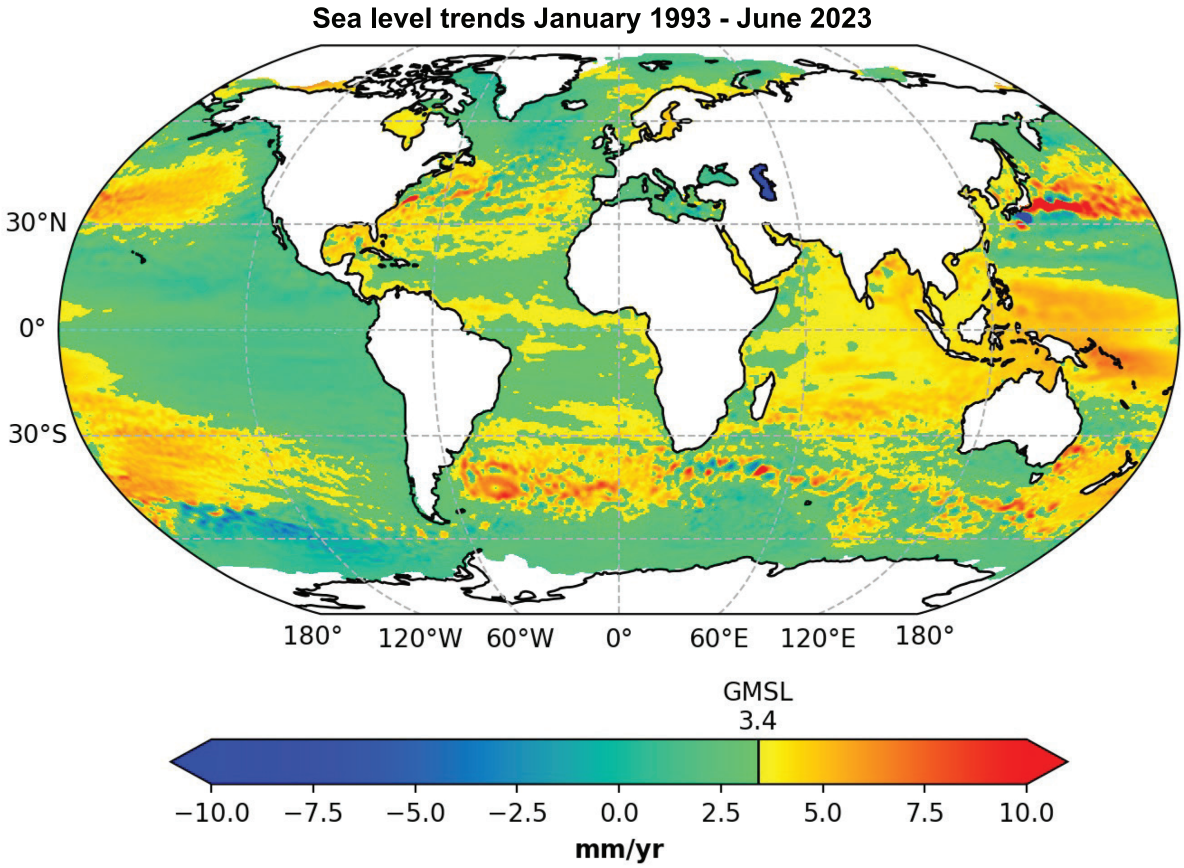

Figure 20. Regional sea level trends (mm/yr) from January 1993 to June 2023, based on multimission satellite altimetry. The colour transition from green to yellow corresponds to the global mean sea level (GMSL) rise. Source: Altimetry data from the Copernicus Climate Change Service.[9]

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Potential of marine carbon dioxide removal (mCDR) to increase the ocean carbon sink

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Introduction

The ocean contains 40 times more carbon compared to the atmosphere (37,100 Pg C as dissolved inorganic carbon vs 900 Pg C – IOC-R, 2021) and hence is a key driver of the global carbon cycle. The ocean component of the global carbon cycle is being perturbed in many ways by climate change. For example, through complex physical processes the ocean, absorbs around 2.7 Pg C yr^{-1} (Gruber *et al.* 2023; Figure 21) and stores ~1.9 Pg C yr^{-1} (IOC-R, 2021), as well as the majority of additional heat released to the atmosphere (IPCC, 2022). Thus, the ocean plays a key role in regulating the global climate. The absorption and transport of heat and carbon dioxide by the ocean is causing a wide range of changes on ocean physics (stratification), chemistry (hypoxia, acidification) with consequent effects on ocean biota (productivity and biogeochemistry) along with a range of carbon cycle feedbacks (altered ability to absorb carbon dioxide) (IPCC, 2022).

Since net zero greenhouse gas emissions targets have become a keystone of climate policy, there has been increasing debate about the need to actively remove carbon dioxide from the atmosphere (termed 'carbon dioxide removal', CDR) in addition to reducing emissions (IPCC, 2022). Since 2020, there has been a surge of interest in marine CDR (mCDR) techniques to store carbon in ocean reservoirs using wide-ranging methods (Table 21). Most interest is currently focused on ocean alkalinity enhancement (which includes electrochemical techniques), sinking biomass (e.g. crop wastes and seaweeds) into the deep ocean and ocean iron fertilization (OIF), which pose many technical, environmental, political, legal and regulatory challenges, among others. This increased interest is reflected in the large continuing increase in the number of scientific papers on mCDR, the growing number of start-ups developing mCDR techniques, the significant funding for mCDR research announced by the US and the EU in 2023[10] and the current consideration of potential regulation of several mCDR techniques by the London Protocol Parties.[11]

Description of findings, trends, status

As the technical and political challenges of the land-based CDR approaches are becoming more apparent, the oceans seem to be becoming the new 'blue' frontier for enhanced carbon drawdown strategies. This has led to significant number of field trials[12] covering artificial upwelling, biomass sinking, direct ocean capture and ocean alkalinity enhancement.

For all the proposed wide range of mCDR techniques, their potential to enhance the ocean carbon sink is largely unknown and based on model simulations (Table 4). Major unknowns include how they will interact with the ocean carbon cycle and whether these interactions will lead to feedbacks (Figure 21). These unknowns are superimposed upon uncertainties on constraining the magnitude of the present day ocean carbon sink that is influenced by internal forcing such as El Niño (Figure 21). These findings demonstrate that without improved understanding of how the ocean sequesters carbon, it will be difficult to establish a baseline, or at the very least a benchmark (Boyd *et al.*, 2023), with which to assess the efficacy of a range of mCDR methods. A range of confounding factors can propagate additional uncertainties. These include the concurrent deployment of different mCDR approaches, each with potentially unknow side-effects (i.e. sign and magnitude) (Figure 21, panel a) overlaid on emissions reductions, carbon cycle feedbacks (such as ocean buffering capacity), the influence of terrestrial CDR (Keller *et al.*, 2018) and the interplay of external forcing (climate change) on internal forcing. The cumulative effect of these carbon cycle unknowns means that robust monitoring, reporting and verification (MRV) is essential to quantify any enhancement of the ocean C sink by mCDR approaches.

However, MRV of mCDR remains very technically and politically challenging, especially on the high seas (Boyd *et al.*, 2023) – significant advances in sustained large-scale ocean monitoring would be needed to be able to detect and attribute the enhancement of long-term marine carbon

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[10] See https://time.com/6328555/energy-department-funding-ocean-carbon-capture-research/, https://oceanacidification.noaa.gov/fy23-nopp-mcdr-awards/ and http://arpa-e.energy.gov.

[11] See https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/LC-45-LP-18.aspx.

[12] See https://oceanvisions.org/mcdr-field-trials/

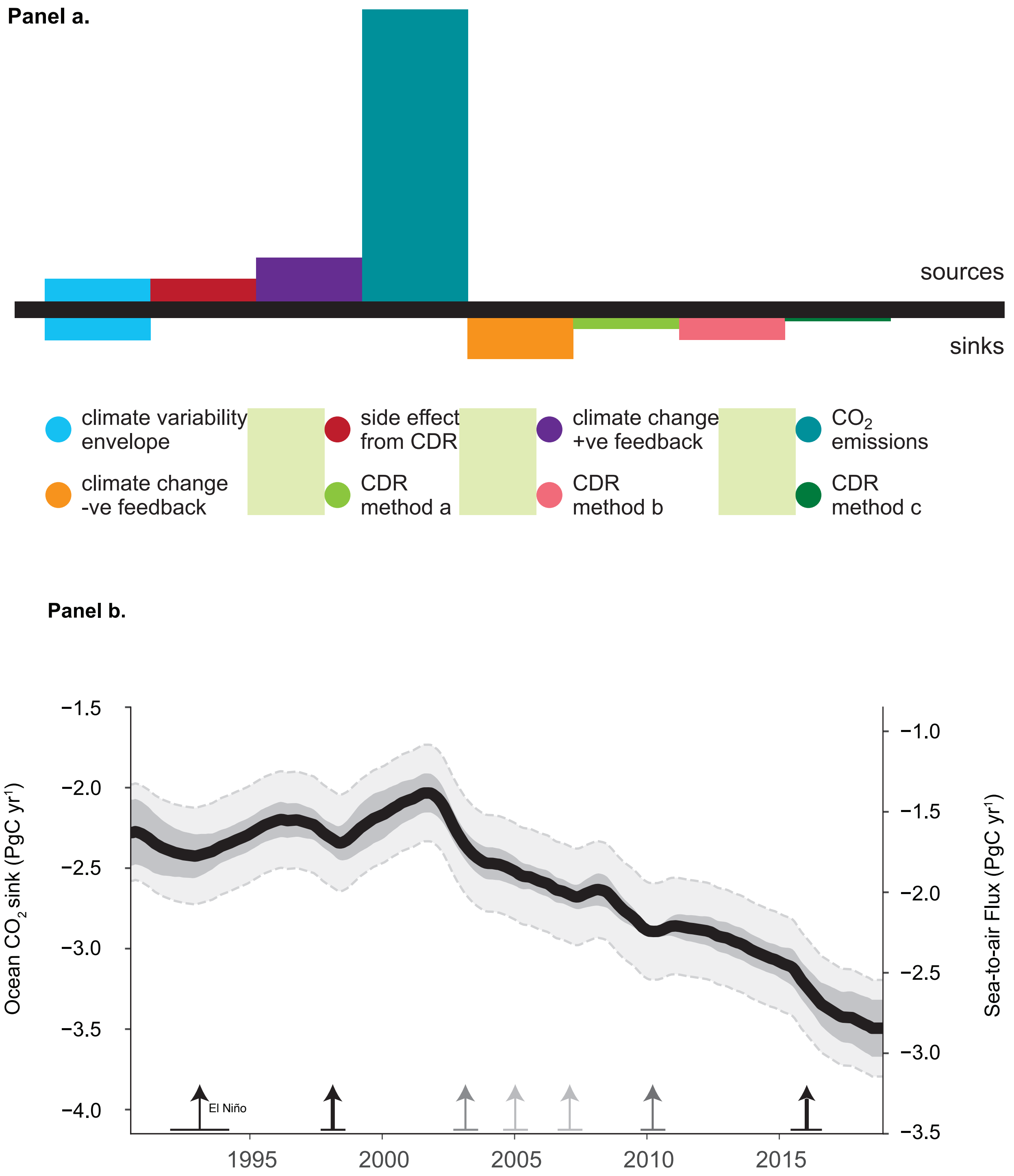

Figure 21. Confounding issues around detection and attribution of alteration of the ocean carbon sink by mCDR methods. Sources: Panel a. – modified from Boyd and Bressac (2017); panel b. – modified from Figure 3 in Gruber *et al.* (2023). Notes: **Panel a**. denotes a range of naturally occurring and/or climate-change driven changes to ocean carbon sinks or sources which will place important constraints and sets thresholds on the detection and attribution of multiple mCDR activities. Owing to many unknowns, it is problematic to provide scalebars for each panel, but note the Pg C year^{-1} scale in panel b. of reported changes along with the error estimates for the ocean carbon cycle. **Panel b**. The black line is the mean estimate of the global ocean CO_2 sink estimates by six ocean partial pressure of CO_2 (pCO_2) observation-based products contained in Seaflux (Fay *et al.*, 2021). The dark grey regions denote the standard error across the six products. Grey dashed lines are the uncertainty estimates for the ocean sink that incorporate that associated with the river outgassing flux. The timing of El Niño events in the Pacific are denoted by vertical arrows (darker arrows are stronger events).

Table 4. Examples of marine CDR approaches in five categories along with their modelled potential to act as oceanic C sinks

Category	Prominent example	Sources of evidence-based knowledge (potential for C sink)	Nature of field studies	Knowledge gaps	Wider applicability of OF regulations
CDR – biology	Ocean iron fertilization (OIF)	Theory, natural analogues, modelling (~10% of current CO_2 emissions, Keller *et al.*, 2014, but see Tagliabue *et al.*, 2023), field studies	Unconstrained, transient, 100 km scale, not legal	Detection, attribution, upscaling issues, side effects	Regulated by the LC/LP
CDR – physical transport	Liquid CO_2 on the Seabed	Theory, natural analogues, field studies	Unconstrained, transient, m scale	Upscaling issues, side effects	Not applicable Banned by the LP but LC position uncertain,
Hybrid technologies for CDR/ food security	Ocean afforestation	Theory, natural analogues, modelling (<<10% of current CO_2 emissions, based on Wu *et al.*, 2023 but constrained with Paine *et al.*, 2023), field studies	Unconstrained, transient, < 5 km	Upscaling issues, side effects	Many differences from OIF, likely limited to coastal ocean (Iron limitation, Paine *et al.*, 2023)
CDR – geochemical	Ocean alkalinization	Theory, natural analogues, modelling (~10% of current CO_2 emissions, Keller *et al.*, 2014), lab tests, field studies	Unconstrained, transient, 10 km scale	Detection, attribution, upscaling issues, side-effects	Parallels, large -scale transboundary issues
CDR – physical transport and biogeochemistry	Artificial upwelling	Theory, natural analogues, modelling (<10% of current CO_2 emissions, Keller *et al.*, 2014), field studies	Tests - from catastrophic failure (< 1 day) to 35 days	Detection, attribution, upscaling issues, side effects	Parallels, large -scale transboundary issues

Source: Modified from summary table in GESAMP (2019).

storage (Frenger *et al.*, 2024) by mCDR. Such detection and attribution for open ocean mCDR methods that rely upon enhancing carbon sequestration (Table 4) must also overcome additional challenges given that the ocean, and its ability to sequester carbon, is already changing (Wang *et al.*, 2023).

In the coastal ocean, there is much interest in restoring/ expanding coastal blue carbon habitats (mangrove forests, seagrass meadows and tidal saltmarshes) to increase sequestration of carbon. However, concerns have been raised about the reliability of the data on CO_2 removal using coastal blue carbon restoration, as it has questionable effectiveness (Williamson and Gattuso, 2022). The restoration of coastal blue carbon ecosystems is nevertheless highly advantageous for climate adaptation, coastal protection, food provision and biodiversity conservation.

Conclusions and next steps

Recent syntheses have revealed that there is still much being learned about how the ocean sequesters carbon (Gruber *et al.*, 2023). For example, the estimated magnitude of the C sink in the Southern Ocean and other ocean provinces has altered significantly over the last two decades (see Figure 3 in Gruber *et al.*, 2023). In the Southern Ocean, where there is interest to deploy some mCDR methods such as OIF at scale, major knowledge gaps include the role of the winter physics and summer biology in setting the magnitude of the carbon sink (Hauck *et al.*, 2023).

The surge of interest in (mCDR) techniques, poses many technical, environmental, political, legal and regulatory challenges. These techniques are all still at early stages of development with much still to be learned about them and their effects on the ocean carbon cycle before any decisions could be made about large-scale deployment.

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A safe ocean where life and livelihoods are protected from ocean-related hazards

Trends and impacts of warning systems for ocean-related hazards: Outcome vs status

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Introduction

Ocean-related hazards, most notably tsunamis and storm surges, pose significant threats to coastal communities worldwide. These global threats, expected to intensify with climate change and rising sea level, can cause extensive damage to critical infrastructure and homes, disrupt economies and livelihoods, and lead to loss of life, especially with the current growth in coastal population and tourism worldwide. The UN Decade of Ocean Science for Sustainable Development (2021–2030) outcome of a 'Safe Ocean' aims to build up coastal resilience from ocean hazards, necessitating the enhancement of multihazard early warning systems by utilizing recent advancements in technology, along with a growing emphasis on community preparedness and resilience.

Large tsunamis travel across entire ocean basins, striking coastlines with little or limited lead time. Nearly 90% of tsunamis have been generated by large earthquakes or landslides triggered by earthquakes.[13] The 2004 Indian Ocean and 2011 Japan tsunamis generated by subduction zone megathrust-earthquakes are the most devastating natural disasters in history, claiming tens of thousands lives with billions of dollars of damages. However, tsunamis produced by non-seismic sources, such as volcanic eruptions or meteorological disturbances, have proved to strike significantly more often than previously thought and have also resulted in severe loss of life and property – the most notable event being the recent Hunga Tonga–Hunga Ha'apai tsunami (Angove *et al.*, 2021; Borrero *et al.*, 2023; Lynett *et al.*, 2022). All of these demand the implementation of emerging observational techniques in tsunami warning systems.

Description of findings, trends, status

Presently, the Global Tsunami Warning and Mitigation Systems, coordinated by IOC-UNESCO covers the world's major ocean basins: the Pacific (PTWS), the Indian Ocean (IOTWMS), the Northeastern Atlantic, Mediterranean and connected seas (NEAMTWS), and the Caribbean and Adjacent Regions (CARIBE-EWS). Approximately 150 countries and territories are contributing to the

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[13] See National Geophysical Data Center/World Data Service: NCEI/WDS Global Historical Tsunami Database. NOAA National Centers for Environmental Information. doi:10.7289/V5PN93H7 (accessed 20 December 2023).

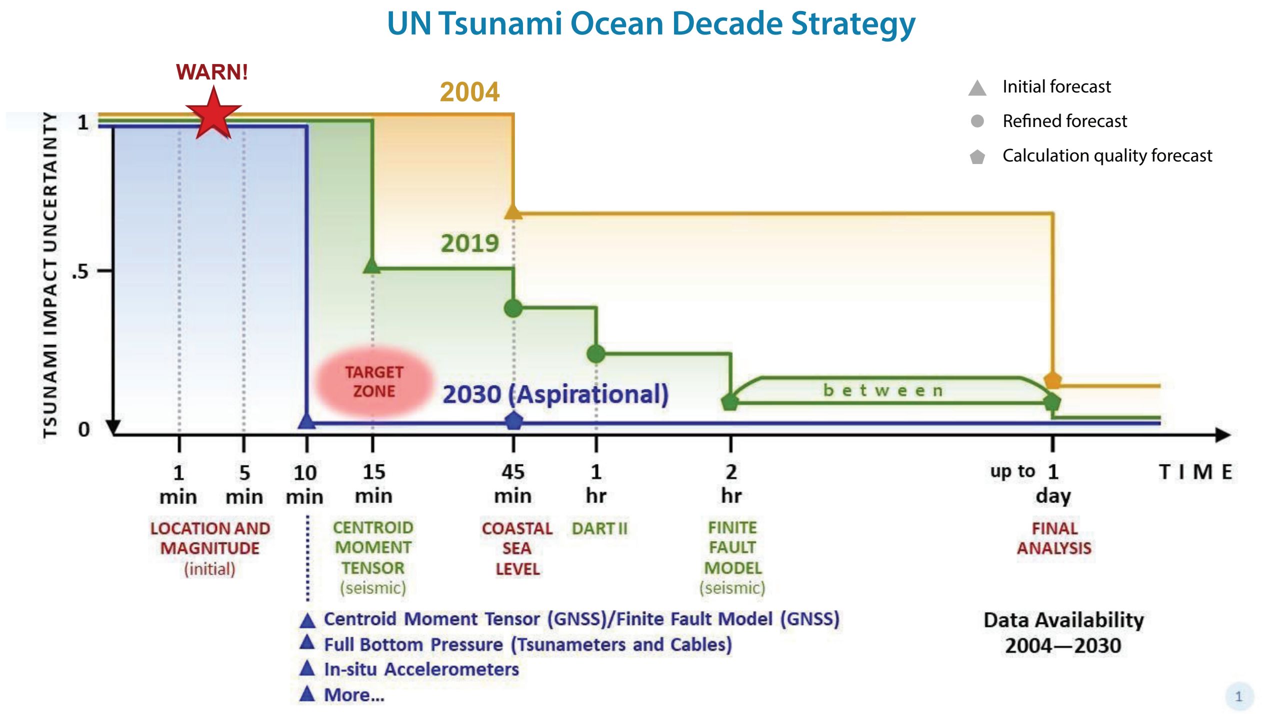

Figure 22. Generalized relationship between tsunami source uncertainty and time after earthquake origin for three different time frames.
Notes: Orange line: tsunami source uncertainty levels prior to 2004; green line: tsunami source uncertainty levels at present (2019); blue line: tsunami source uncertainty levels achievable with the ocean sensing and analysis techniques.

Source: Updated from Angove *et al.* (2019).

global efforts in tsunami hazards resilience. The status of warnings for tsunamis has seen considerable advancement in the past decade, but the aspiration is to further improve (Figure 22; Angove *et al.*, 2019). The estimation of earthquake forcing mechanisms can be obtained between 2–3 hours, and sometimes much sooner (~15 min). An increasing network of state-of-the-art monitoring infrastructure, including tens of thousands seismometers, 74 deep-ocean tsunami buoys, about 1,234 active sea level stations shared through the UNESCO Sea Level Station Monitoring Facility tide gauges (in 2022 1,043 seal level stations were in place) and several submarine cable observatories are now available to detect and measure large tsunamis with sufficient lead time to alert distant coastlines (Figure 23). The expansion of the Deep-Ocean Assessment and Reporting of Tsunamis (DARTs) network, in particular New Zealand's new deployments, played a vital role in assessing the tsunami threats of the Tonga volcanic eruption (GNS Science, 2022). Moreover, advancements in satellite-based remote sensing technologies, such as the Global Navigation Satellite System (GNSS) and ionospheric-disturbance detection (Martire *et al.*, 2023), will further enhance the capability of tsunami detection and early warning system with increased precision. The UN initiative on Science Monitoring and Reliable Telecommunications (SMART) subsea cables (Howe *et al.*, 2019 and 2022) has facilitated the installation of the SMART Wet Demonstration system off the coast of Italy. Two contracted SMART systems, one connecting Vanuatu and New Caledonia and the other off Portugal, will be ready for service in 2026. Support for these come from the European Union (Digital Connectivity) and respective governments, development banks, foundations and companies. Equipped with sensors measuring pressure, seismicity and temperature, SMART cables aim for direct in situ early detection of earthquakes and tsunamis for regions not covered by the sparse distribution of tsunami buoys. The rapidly growing field of optical fibre sensing in submarine cables, including distributed acoustic sensing (DAS), is showing potential for detecting tsunamis (Xiao *et al.*, 2024). Algorithms relying on underwater earthquake-derived acoustic signals are also emerging for rapid source determination of tsunamis (Gomez and Kadri, 2023) and undersea acoustic communication methods are being used to transfer near-shore bottom pressure data to land (Comfort and Rahayu, 2023).

Monitoring and predicting storm surges is crucial to provide valuable information for early warning of severe weather events and emergency response efforts. Tropical cyclones and storm surges are monitored by a variety of

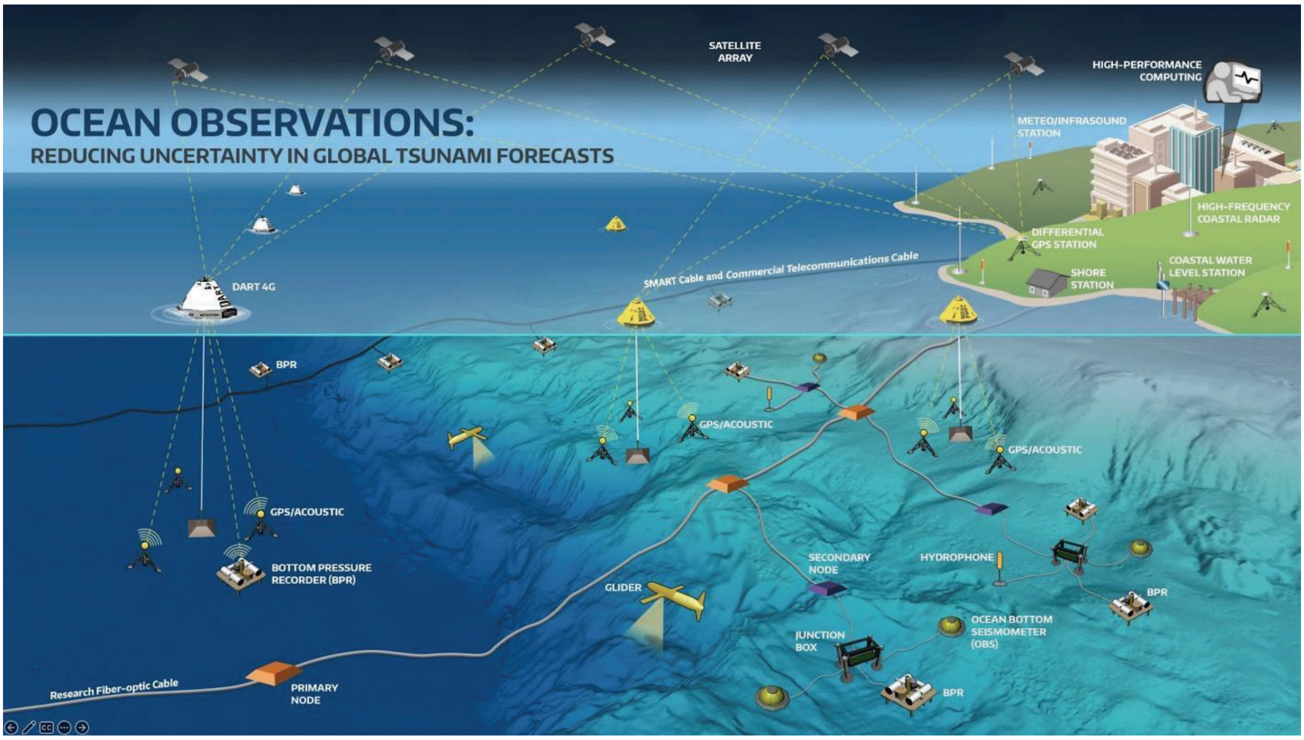

Figure 23. Existing and emerging ocean observational technologies for global tsunami forecasts. Source: Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration.

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). Aircraft, satellites, drones and unmanned aerial vehicles (UAVs) are now commonly used technologies in hurricane tracking, with data from them being used as real-time input for the model forecast system. The storm surge level is usually monitored by a range of tools, including tide gauges, coastal radar systems, satellite remote sensing and ocean buoys.

One notable trend in response systems for ocean-related hazards is the integration of real-time data from various observational sources into advanced and unified model simulation platforms, which are moving to the next generation, featured by global coverage, probabilistic ensembles and three-dimensional realizations, as well as impact-based forecasting. In the United States, the National Oceanic and Atmospheric Administration (NOAA) is currently implementing this integration to enable more accurate and timely predictions of extreme flooding impacts, encouraging early action and empowering decision-makers to implement targeted evacuation orders and emergency response plans. In hazard-prone regions, another prominent trend is the growing emphasis on constructing resilient infrastructure and enforcing hazard-resistant building codes for critical facilities such as hospitals, schools and emergency shelters, as well as power plants, airports and ports. The new chapter 'Tsunami Loads and Effects' incorporated in the American Society of Civil Engineers (ASCE) Standard (ASCE, 2017), Minimum Design Loads and Associated Criteria for Building and Other Structures, is the first national, consensus-based standard for tsunami-resilient building design in the US. This standard was also included in the requirement of the 2018 International Building Code (IBC).

The inclusion of community preparedness in warning systems has led to improved public awareness and education regarding ocean-related hazards, in an end-to-end and people-centred early warning system. After extensive piloting, in 2022 the UNESCO Tsunami Ready Program was established. As of early 2024, 48 communities across 23 countries in the Caribbean, Pacific, Indian Ocean and North East Atlantic and Mediterranean regions were recognized for achieving the established indicators. The goal is that by 2030, 100% of tsunami at-risk communities are prepared and resilient to tsunamis through efforts like Tsunami Ready. This will foster a culture of resilience, empowering individuals and communities to take proactive measures to protect themselves and their surroundings during hazardous events, not only tsunamis.

Conclusions and next steps

Enhancing global resilience of ocean-related hazards is currently challenged by limited resources and capacity, urbanization and population growth, and abrupt climate change and sea level rise. The UN Decade of Ocean

Science (2021–2030) with an emphasis on a 'Safe Ocean' is an opportunity to apply science, technology and innovation and the best available knowledge to develop conventional and innovative solutions for effective preparedness and response.

The Ocean Decade Tsunami Programme is one such initiative under the UN Ocean Decade that provides a framework for collaboration among all relevant stakeholders to enhance resilience to tsunami and other ocean hazards (IOC-UNESCO, 2023).

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Harmful algal bloom impacts increase amid rising sea food demand and coastal development

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Introduction

Among the approximately 35,000 species of marine phytoplankton in the world's oceans today (Guiry, 2024), some 200 taxa produce toxins that can threaten seafood safety and human health, cause mortality of wild or aquaculture fish and impact on coastal tourism and recreation (Lundholm *et al.*, 2009). Non-toxic microalgae attaining high biomass can also cause harmful algal blooms (HABs) by producing seawater discolorations, mucilage and/or anoxia, which negatively affect the environment, human activities and aquaculture, with consequences for well-being and the economy.

Several studies in recent decades have suggested an apparent ongoing geographic expansion, duration and intensification of HABs, with evidence from a number of high-profile cases (Hallegraeff, 1993). Eutrophication, human-induced introduction of alien harmful species, climatic and oceanographic changes 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 prevented a sound global assessment of the current status of HABs.

Description of findings, trends, status

The IOC-ICES-IAEA-PICES Global HAB Status Report (GHSR) (Hallegraeff *et al.*, 2021a,b,c; Zingone *et al.*, 2021a), supported by the Government of Flanders and hosted within the IOC-IODE, compiled the first overview of HAB events and their societal impacts. The GHSR initiative 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 IOC-ICES-PICES HAEDAT (Harmful Algal Event Database) collecting events produced by toxic or non-toxic species that exert impact on human health or activities, or the environment (Zingone *et al.*, 2021b). HAEDAT is based on a strict definition of a harmful algal bloom event as having a demonstrated negative impact on ecology or human society. This differs from regional data bases such as HAATC (Harmful Algae and Algal Toxins in coastal waters of China) which are dominated by high biomass bloom events (such as water discolorations) but often without records of impacts on society. The IOC-UNESCO Harmful Algal Information System (HAIS) mapping application allows for any combination of species occurrence (OBIS/HABMAP) and event data (HAEDAT) (Figure 24). A separate IOC-UNESCO Toxins Database, currently under development, will ultimately be linked to HAEDAT.

Regional overviews compiled by 109 scientists from 35 countries based on the IOC 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. The first global scale statistical analyses of HAEDAT records (9,503 events in the period 1985–2018) used the OBIS phytoplankton dataset (5,944,392 microalgal records, including 289,668 distribution records of harmful species) as a proxy for observational efforts. This work 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, thus refuting the perception that HABs are increasing in frequency globally. Observed trends from these datasets were variable and contrasting among different regions, 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, resultant impacts vary from region to region. Thus, trends and patterns of HABs 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

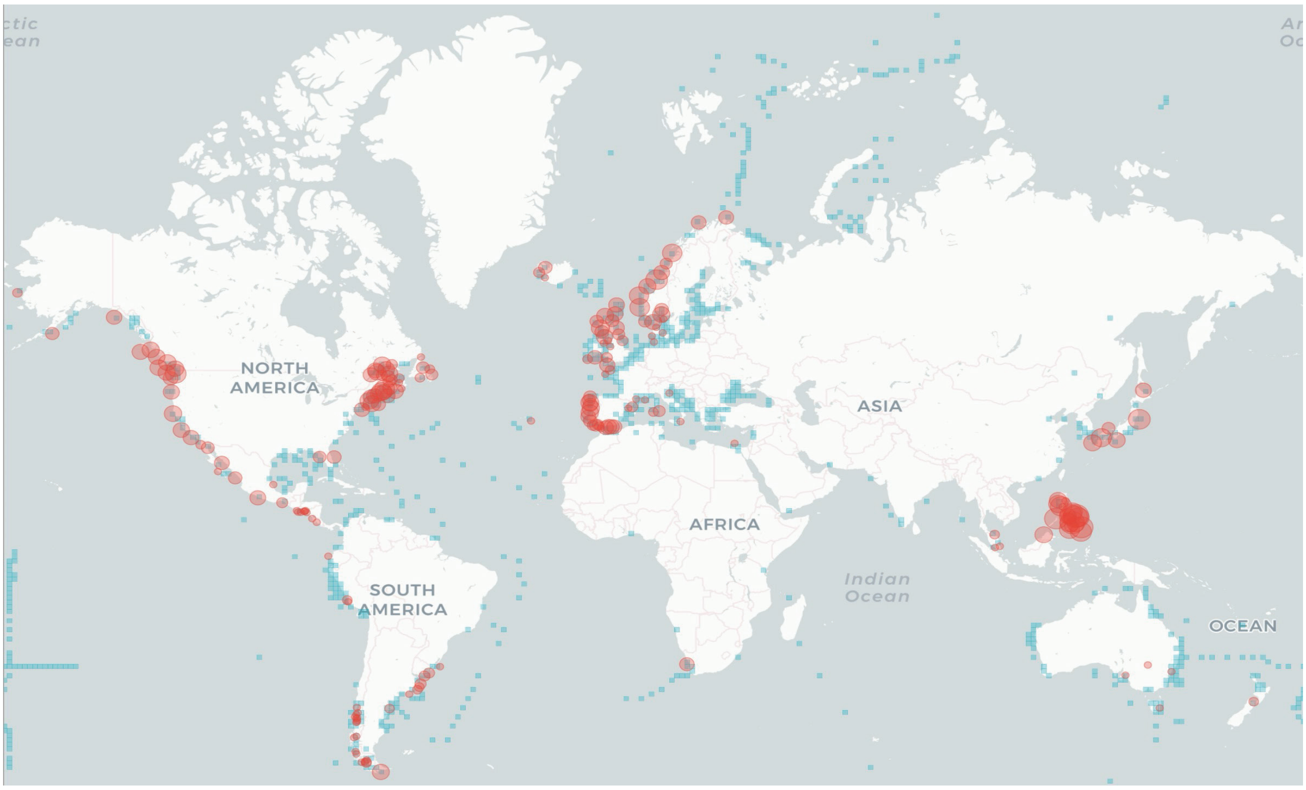

Figure 24. World map of distribution events associated with paralytic shellfish toxins (red) combined with that of the occurrence of Alexandrium causative organisms (blue). Source: Based on data obtained from the HAIS Data Portal https://data.hais.ioc-unesco.org/. The larger the bubbles, the more events were observed in a locality.

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 increased monitoring effort associated with the development of aquaculture operations in coastal areas (Hallegraeff *et al.*, 2021c) (Figure 25), leading to the conclusion that the latter is the source of the perceived increase in harmful algae events. Hence, while there is no empirical support for increasing global trends, the link observed between aquaculture-driven monitoring and HABs trends indicates that HAB impacts will become increasingly evident in parallel with the rising demand for sea food and expansion of aquaculture industry. A subsequent GlobalHAB roadmap report on fish-killing marine algal blooms (Hallegraeff *et al.*, 2023) further highlights the need for better data-sharing between industry and scientists, as regulatory authorities, the seafood industry, tourism and recreational users increasingly demand more confidence in predicting blooms and to manage them in order to minimize their impacts.

Conclusions and next steps[14]

Since its publication, the GHSR has supported numerous follow-up studies, being accessed 27,000 times and cited 200 times (Web of Science[15]). Next steps will focus on the incorporation of new datasets and refinement of the databases to ensure that OBIS/ HABMAP and HAEDAT remain a global resource for managers, scientists, industries and policy-makers working with HABs and their impacts to ensure sustainable use of the world's oceans.

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14 See https://data.hais.ioc-unesco.org

15 See https://www.webofscience.com/wos

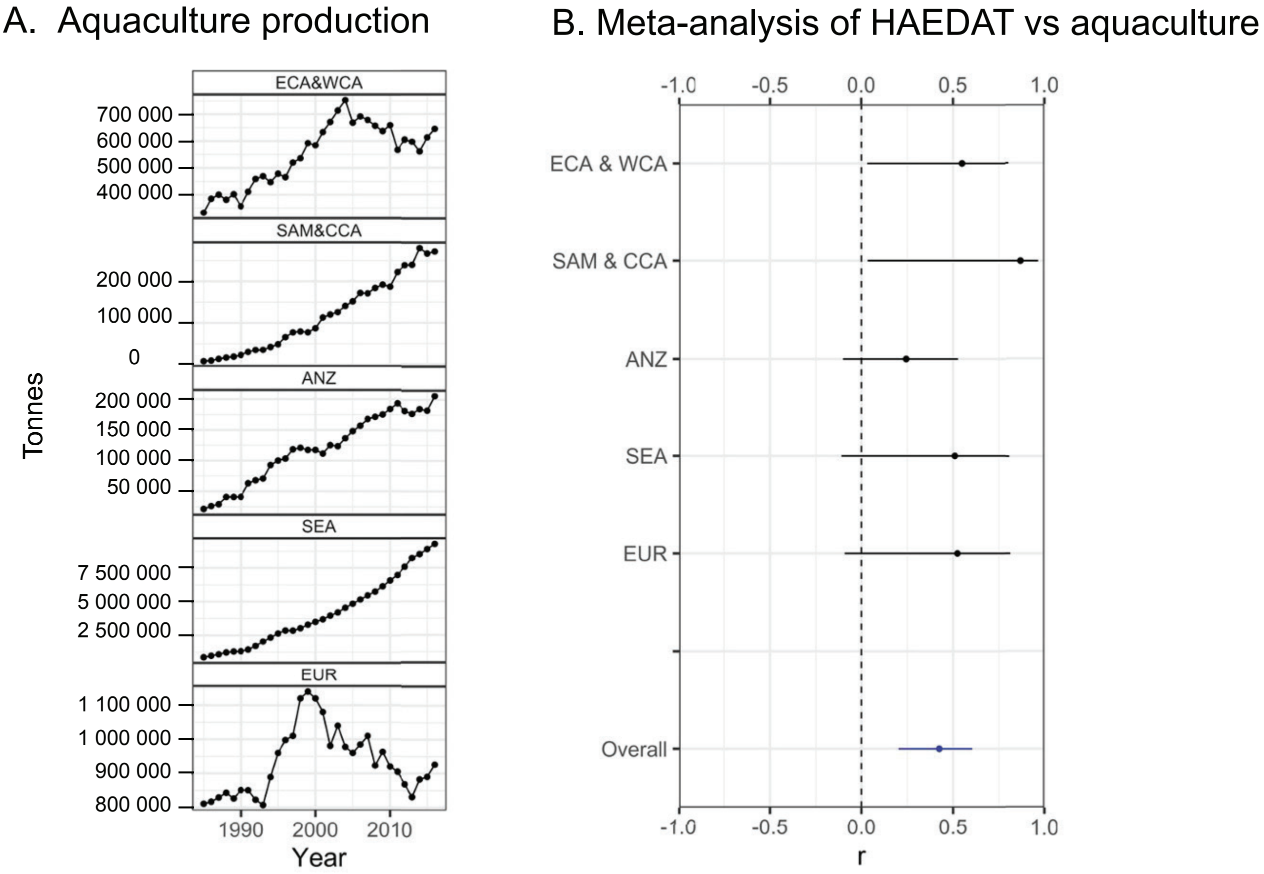

Figure 25. Relationship between changes in aquaculture production (from FAO) and harmful algal bloom events recorded in HAEDAT in the period 1985–2018.

Notes: Panel **a**. Changes in five regions (East and West Coast America (ECA & WCA); South America, Central America, Caribbean (SAM & CCA); Australia and New Zealand (ANZ); South-East Asia (SEA); Europe (EUR)) of tonnage of aquaculture production of fish, molluscs, crustaceans and aquatic plants; panel **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 (blue lines).

Source: Harmful Algal Events Database (HAEDAT)[14]; Hallegraeff *et al.* 2021*c*.

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Additional resources

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

OBIS https://www.obis.org

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An accessible ocean with open and equitable access to data, information and technology and innovation

Global Ocean Observing System status and expansion

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Introduction

The Global Ocean Observing System (GOOS) and the Ocean Decade share a vision for an integrated ocean observing system delivering vital information for sustainable development, safety and prosperity. Key to this vision is connectivity across the value chain – from observations to end-user services – ensuring fitness for purpose across climate, weather, hazard warnings, ocean health and the blue economy.

Numerous ocean information value chains exist. For example, operational services such as weather forecasts rely on data from drifting and moored buoys, Argo floats and voluntary observing ships, transmitted via satellites. This data informs global weather models. Other examples include acoustic whale data used to inform and slow down ships, or informing climate assessments with ocean temperature data.

Ocean data is essential for planning, protecting and managing resources. Without it, communities cannot adapt to climate change, biodiversity loss, create carbon markets, or build sustainable ocean economies. GOOS's work supporting nations in reaching global sustainability goals remains urgent.

Description of findings, trends, status

Through its operations centre OceanOPS, GOOS monitors more than 8,000 observing platforms across 14 global ocean observing networks, operated by 84 countries, that deliver more than 120,000 real time (synoptic) observations daily that are routinely assimilated into numerical models for weather and ocean forecasts, hazard warnings and other predictions (Figure 26). In addition, there are over 600 biological/ecological observing programmes, operated by 71 countries as identified through the GOOS BioEco Portal. These global ocean observing networks also supply calibrated and quality controlled data in 'delayed mode' to global data assembly centres for use in a multitude of climate and ocean health applications (Jolly *et al.*, 2021).

In recent years, there have been advances in the number of networks that have the technical capacity to deliver data into these global data systems, some of these 'emerging' networks use existing private sector infrastructure, such as fishing vessel networks and undersea cables network to advance observation, and others focus on key areas of observing need, such as surface ocean carbon across several types of observing platforms, both positive trends.

Advances have also been made in biological and ecological observing; GOOS has seen a ten-fold increase in the amount of species observations being shared with open platforms like the Ocean Biodiversity Information System (OBIS, see Figure 27), which can be attributed to the development of international standards, coordinated semi-automated data flow pipelines with integrated quality control steps, and new observing technologies related to omics (eDNA), optics (imaging) and acoustics

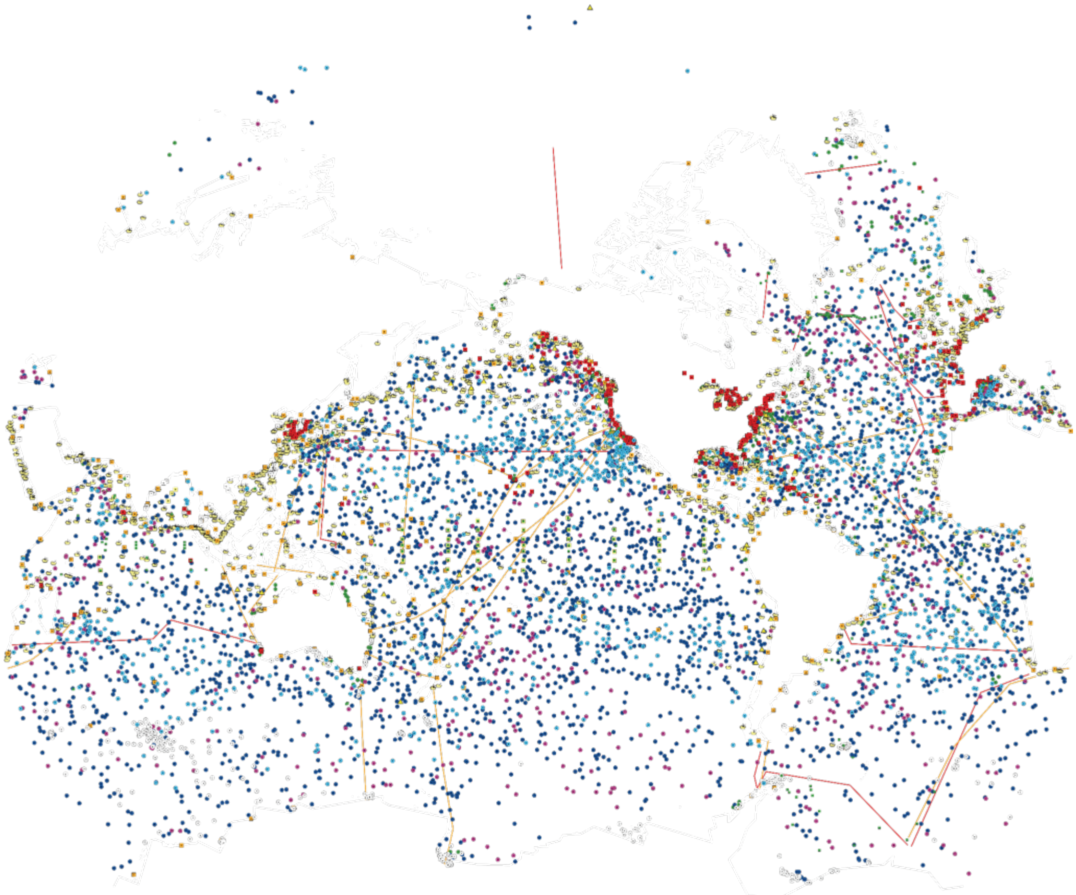


Figure 26. Locations of operational platforms and ships from global in situ ocean observing networks; reference lines sampled since January 2022. Note: Although this forms a visualization of the different networks across the GOOS, this is a representation; the symbols' size is not to scale – in the map they are exaggerated to an order of 100 km for readability, and on any one day and in any one location, as the floats and drifters move and/or ships are sampling, the picture can look very different. The GOOS is dynamic. *Source*: OceanOPS; IOC-UNESCO (2023).

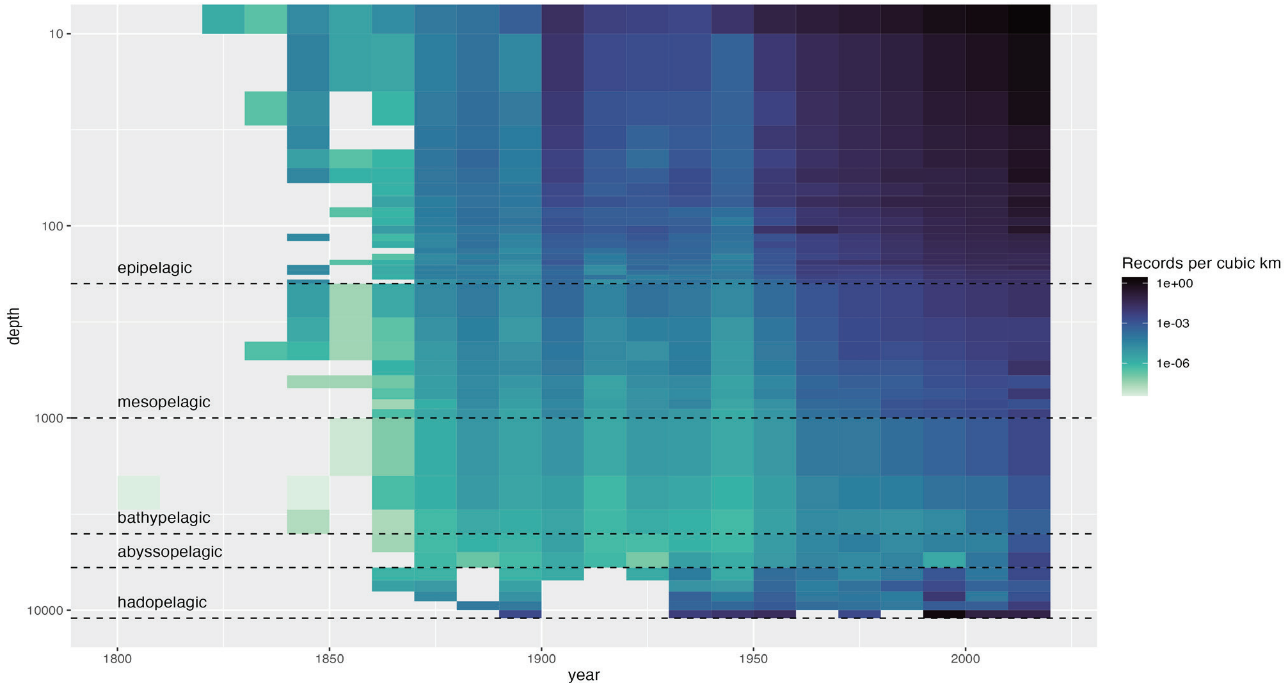
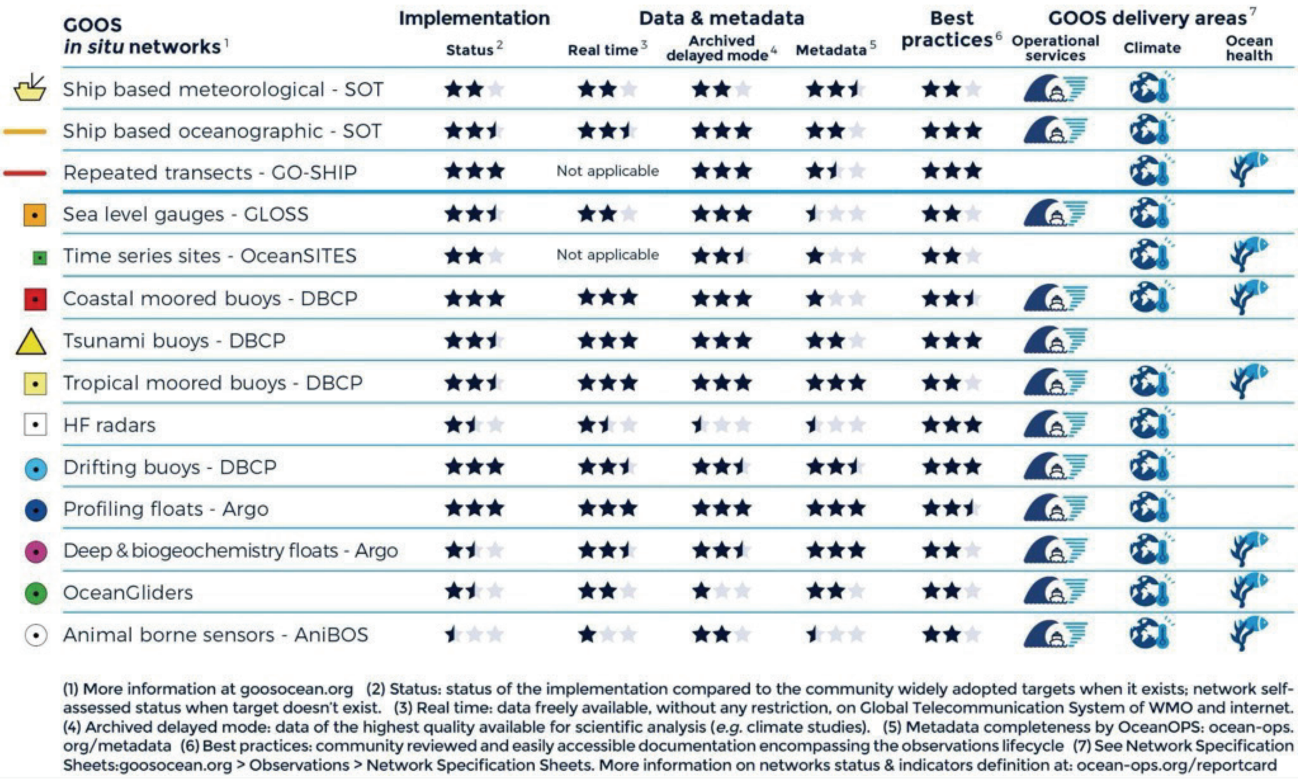


Figure 27. Number of OBIS records per km3 of ocean volume, over time and per depth zone, clearly illustrating the trend of going deeper. *Source*: OBIS.



	GOOS *in situ* networks[1]	Implementation	Data & metadata			Best practices[6]	GOOS delivery areas[7]		
		Status[2]	Real time[3]	Archived delayed mode[4]	Metadata[5]		Operational services	Climate	Ocean health
	Ship based meteorological - SOT	★★☆	★★☆	★★☆	★★⯪	★★☆	✓	✓	
—	Ship based oceanographic - SOT	★★⯪	★★⯪	★★★	★★☆	★★★	✓	✓	
—	Repeated transects - GO-SHIP	★★★	Not applicable	★★★	★⯪☆	★★★		✓	✓
🟧	Sea level gauges - GLOSS	★★⯪	★★☆	★★★	⯪☆☆	★★☆	✓	✓	
🟩	Time series sites - OceanSITES	★★☆	Not applicable	★★⯪	★☆☆	★★☆		✓	✓
🟥	Coastal moored buoys - DBCP	★★★	★★★	★★★	★☆☆	★★⯪	✓	✓	✓
△	Tsunami buoys - DBCP	★★⯪	★★★	★★★	★★☆	★★★	✓		
🟨	Tropical moored buoys - DBCP	★★⯪	★★★	★★★	★★★	★★☆	✓	✓	✓
□	HF radars	★⯪☆	★⯪☆	⯪☆☆	⯪☆☆	★★★	✓	✓	
●	Drifting buoys - DBCP	★★★	★★⯪	★★⯪	★★⯪	★★★	✓	✓	
●	Profiling floats - Argo	★★★	★★★	★★★	★★★	★★⯪	✓	✓	
●	Deep & biogeochemistry floats - Argo	★⯪☆	★★⯪	★★⯪	★★★	★★☆	✓	✓	✓
●	OceanGliders	★⯪☆	★★☆	★☆☆	★★☆	★★☆	✓	✓	✓
○	Animal borne sensors - AniBOS	⯪☆☆	★☆☆	★★☆	⯪☆☆	★★☆	✓	✓	✓

(1) More information at goosocean.org (2) Status: status of the implementation compared to the community widely adopted targets when it exists; network self-assessed status when target doesn't exist. (3) Real time: data freely available, without any restriction, on Global Telecommunication System of WMO and internet. (4) Archived delayed mode: data of the highest quality available for scientific analysis (*e.g.* climate studies). (5) Metadata completeness by OceanOPS: ocean-ops.org/metadata (6) Best practices: community reviewed and easily accessible documentation encompassing the observations lifecycle (7) See Network Specification Sheets:goosocean.org > Observations > Network Specification Sheets. More information on networks status & indicators definition at: ocean-ops.org/reportcard

Figure 28. Legend of main GOOS operational observing networks, as shown on the map (Figure 26), and performance evaluation on status, data/metadata flows, best practices and main GOOS applications areas. *Source*: GOOS.

(passive and active tracking). These changes have also resulted in an increase in observations further off-shore and in deeper waters, including the biologically important mesopelagic zone.

In addition, there have been advances in the development of GOOS-endorsed best practices that cover observing operations and data flow (Figure 28) and in defining an implementation strategy for a cross network data implementation strategy (see 'Open access to ocean data from global to local scales'), all of which contribute to the ensuring that the observations collected are FAIR (findable, accessible, interoperable and reusable).

Despite these advances, growth across the global ocean observing networks as tracked through OceanOPS has been static in recent years. Although the global ocean observing networks (Figure 26) have now almost completely recovered from the impact of COVID-19 on their operations, the combination of inflation and flat national funding mean that although there have been technology advances, there has been no significant growth in observations in the last five years. In addition, although there has been investment in biogeochemical sensors, they still represent only a small fraction of the observing system, for example, only 7.5% of the current system measures dissolved oxygen and this is even less for other biogeochemical variables. To provide society with the baseline information needed, for example to track carbon effectively, we will need a significant increase in biological and biogeochemical observations.

Persistent gaps in the ocean observing system, both spatially and thematically, remain and there is also a growing urgent societal need for more ocean observations to manage risk and adapt to change in ocean and weather systems and support sustainable blue economic growth. The recent Ocean Decade Vision Paper on Expanding the Global Ocean Observing System noted a number of these gaps and urgent needs, including: polar regions, the global south, island nations and priority coastal systems, plus an urgent need to address extreme weather events, coastal hazards, marine biodiversity and ocean health, and increasing demand for more data to support investment in and management of a sustainable ocean economy (Vision 2030 Working Group 7, 2024). For example, there are challenges to effectively track and forecast marine heatwaves and extreme weather events, including tropical cyclones, storm surge and flooding.

Across physical, biogeochemical and biological and ecological observations, there remains a strong north/south bias and persistent observing gaps in the remote and technically challenging polar regions, for island nations with very large ocean areas to GDP ratios and priority coastal systems. For example, Figure 26 indicates that the south hemisphere is less covered by observing systems, and for example at the network level the coverage for global arrays of floats and drifters as tracked through OceanOPS, shows that while the North Atlantic is consistently over capacity (vs. target), the Indian Ocean is under capacity and was impacted more strongly during the pandemic.

Finally, the tracking of GOOS capacity is incomplete and a number of coastal, regional, national initiatives, including sustained biological and ecological observing initiatives, are not yet fully integrated. Despite advances, data sharing is still not ubiquitous, across private and government sectors. Sharing existing data streams is as important as developing new; this can be an issue of communication, capacity and of trust. These limit the data available to users, the persistence and interoperability of the data, but also the visibility of investments in these observations and the ability to assess adequacy of the system to meet societal needs.

Conclusions and next steps

To address these challenges, there are several key areas of work that GOOS and the global observing community can focus on:

Use co-design projects and activities, with a focus on areas of high societal need and where ocean observations can have significant impact, to expand fit for purpose observations and to connect across the value chain, ensuring that ocean information reaches users and meets main societal challenges. Current work through the GOOS Ocean Decade Co-Design Programme and for coastal areas through CoastPredict Programme are important global initiatives under the Ocean Decade, and are addressing thematic and geographic coverage, as well as embedding co-design and partnership along the value chain.

Build a stronger digital infrastructure to better track observations globally, assess fit for purpose and support delivery of data (see 'Open access to ocean data from global to local scales').

Develop new thinking around investment for ocean observing, to address the persistent inequality in observing capability; states with large ocean areas under national jurisdiction to GDP ratios will require support to implement the observations that they and global society require. The WMO Systematic Observations Finance Facility (SOFF) provides an example of how to target funds towards sustained observations that complement countries' capabilities and needs. Greater cooperation between public and private sector towards growing ocean observing and a vibrant Ocean Enterprise sector, as envisioned in the work of the Dialogues with Industry Initiative (see 'Involving civil society and the private sector in the Global Ocean Observing System ') will help establish ocean observing as an economic sector and critical infrastructure, and raise the opportunity for private sector collaboration in solutions.

The future GOOS will need a stronger infrastructure and workforce, and strong partnerships to effectively support and coordinate a system responsive to end-users and to science. Greater collaboration with partners, including industry, across the value chain and within the UN Ocean Decade is an important opportunity to reach these goals.

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Jolly, C., Jolliffe, J., Postlethwaite, C. and Heslop, E. 2021. *Value Chains in Public Marine Data: A UK Case Study*. OECD Publishing, Paris. (OECD Science, Technology and Industry Working Papers, No. 2021/11.) https://doi.org/10.1787/d8bbdcfa-en.

Vision 2030 Working Group 7. 2024. *Vision 2030 White Paper: Challenge 7 – Sustainably Expand the Global Ocean Observing System*. Paris, UNESCO.

Additional resources

GOOS Bioeco - portal https://bioeco.goosocean.org/

OceanOps https://goosocean.org/who-we-are/observations-coordination-group/oceanops/

OBIS https://obis.org/

Ocean Best Practices https://search.oceanbestpractices.org/

Open access to ocean data from global to local scales

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Introduction

At a time of planetary climate crisis, we need relevant, timely, reliable and accessible ocean data, information and knowledge. Achieving the Ocean Decade's 2030 vision of 'the science we need for the ocean we want' requires an enabling digital environment – including the frameworks, infrastructure, tools, capacity and resources – for a distributed ocean information ecosystem that connects across disciplines and geographic boundaries.

It is clear that ocean stakeholders face significant challenges in finding, accessing, using and understanding ocean data. Though there has been incremental progress over the past years, there is a step change needed to truly create a trusted, inclusive and interconnected ocean data and information system that is actively used for decision-making to support sustainable management, but that also allows for new data sources, information networks and solutions to be integrated as the Ocean Decade needs evolve.

Description of findings, trends, status

The monitoring of the GOOS data flow (Figure 27) by OceanOPS tells us that 90% of these 120,000 daily observations reach operational users through the Global Telecommunications System (GTS) of the World Meteorological Organization (WMO), a measure of near-real time data flow. However, we lack high quality metadata for 23% of these observations which impacts their usability. About 10–15% of these observations are rejected by numerical models quality controls. A transition towards global web-based data nodes is underway, but not yet completed across the GOOS networks, and so data access to near-real time data is not yet fully democratized. The data flow pathway for high quality, delayed mode data is distinct from the operational near-real time data and as a result access is traditionally less harmonized and the GOOS monitoring capacity less complete. However, federated data nodes will allow for better tracking of both near-real time and delayed mode data delivery across its networks and from the 84 countries that contribute to the global system. Biological data are published in the Ocean Biodiversity Information System (OBIS) by over 1,000 institutions from 99 countries, of which 16 are African countries and 21 SIDS. On average, OBIS grows by 50,000 observations per day and currently integrates over 120 million observations of 183,000 marine species, which covers 75% of currently known marine species.

A number of countries need assistance to distribute their data and metadata according to international standards; however, the international community lacks a central technical support infrastructure to assist and broker the raw data to the existing data processing nodes, hence this data is currently missing from the global view. This function is today run on an ad hoc basis through GOOS OceanOPS, but needs to be strengthened to be more efficient, for example, through the use of open-source tools, shared code and data processing libraries. Future use of AI tools and utilities will play a significant role in the future but are not in wide use currently.

In the past two years, there has been significant work to not only codify the vision of a truly accessible ocean digital ecosystem, but also to provide actionable implementation steps for moving in that direction. One such strategy was The UN Ocean Decade Data and Information Strategy, which was the work of two dozen domain experts who developed an overarching data and information strategy to support the Ocean Decade (IOC-UNESCO, 2023).

Focusing further on improving GOOS data flows, the GOOS Observations Coordination Group (OCG) also released its Cross-Network Data Implementation Strategy (Figure 29; GOOS, 2024). The goals of this data implementation strategy are to improve integration of data and metadata and to provide FAIR compliance for metadata, data and data access services across the thirteen OCG global in situ networks and align with the objectives of the broader data strategies. This includes the goal of enhancing data discovery and accessibility in close partnership with the International Oceanographic Data and Information Exchange (IODE) and through their Ocean Data Information System (ODIS). It is important to improve links between the data activities of the coastal and global oceans for both operational and research activities and to ensure data connections to regional data hubs.

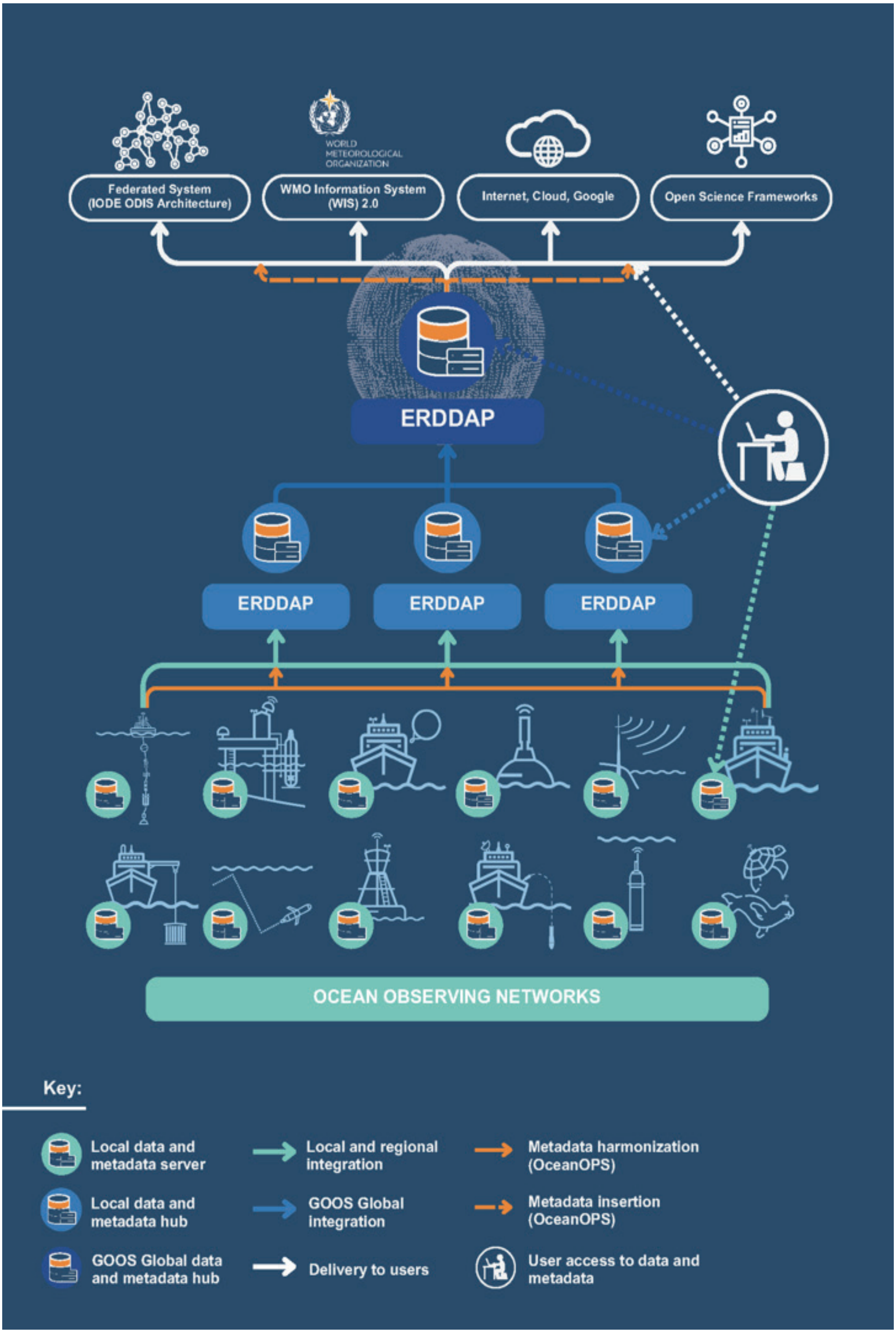

Figure 29. A schematic of the proposed GOOS OCG federated data system which provides local, regional and global access to distributed data and metadata resources. Source: GOOS OCG Cross-Network Data Implementation Strategy.

Conclusions and next steps

Though there has been significant progress in defining strategies to improve global ocean data access, the implementation of these strategies in a unified way is critical in order to strengthen ocean observing data flows. As GOOS builds its federated network of data nodes to unify the data and metadata available through a machine-to-machine (M2M)-ready architecture, we must also track progress towards meeting requirements. The GOOS OCG is refining their metrics to do just that. The improved frameworks will allow for exchange of quality metadata with OceanOPS, add value to datasets produced and eventually flow into WMO and IOC discovery catalogues, such as OSCAR and ODIS, ready to support new services such as digital twins and other future forward applications. Lastly, it is also critical to highlight the need to increase the ocean data workforce in order implement the strategies designed to improve these data flows. Without a more diverse, engaged workforce, this work will not be possible.

References

IOC-UNESCO. 2023. *Ocean Decade Data & Information Strategy*. Paris, UNESCO. (The Ocean Decade Series, 450) Available at: https://unesdoc.unesco.org/ark:/48223/pf0000385542

GOOS. 2024. *GOOS Observations Coordination Group Cross-Network Data Implementation Strategy.* (GOOS Reports, 295 v1.7.) Available at: https://goosocean.org/document/33970

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

Lucy Scott,[1] Ward Appeltans,[1] and Peter Pissierssens[1]

[1] Intergovernmental Oceanographic Commission of UNESCO

Introduction

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 2021–2030 (Ocean Decade) and beyond.

Ocean data represents an economic opportunity, as focus globally is shifting towards sustainable use of the ocean. Data sharing is essential 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 and knowledge we are already collecting and generating about our oceans.

Description of findings, trends, status

A key element needed to ensure equitable global sharing of data and information is free and open access, and for this reason the Intergovernmental Oceanographic Commission (IOC) of UNESCO adopted the revised IOC data policy and terms of use (IOC-UNESCO, 2023) taking into consideration the new requirements of the Ocean Decade. The policy recommends meeting FAIR and CARE (collective benefit, authority to control, responsibility, ethics) principles, licensing, using data repositories such as ODIS (IOC Ocean Data and Information System) as well as secure long-term data archives. It also calls for minimum restrictions on use and for the development of data and metadata sharing guidelines. Another important reference is the UNESCO Recommendation on Open Science (UNESCO, 2021).

The programme International Oceanographic Data and Information Exchange (IODE) of the 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 countries and by meeting the needs of users for data and information products.

The IODE community comprises a global network of 102 data centres in 65 countries (Figure 30). These centres 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, IODE developed 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.

Conclusions and next steps

Since the creation of the internet and World Wide Web, 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 System (ODIS), an e-environment (ocean data ecosystem) where users can discover data, data products, data services, information, information products and services provided by countries, projects and other partners associated with 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 high diversity of products and services, while maintaining its core functions. The ODIS architecture has been established and currently indexes 32 databases from 28 partner organizations. The above mentioned network of IODE data centres will gradually be linked into ODIS.

The IOC Ocean InfoHub Project (OIH) has facilitated the development of the first phase of the ODIS architecture through engaging 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

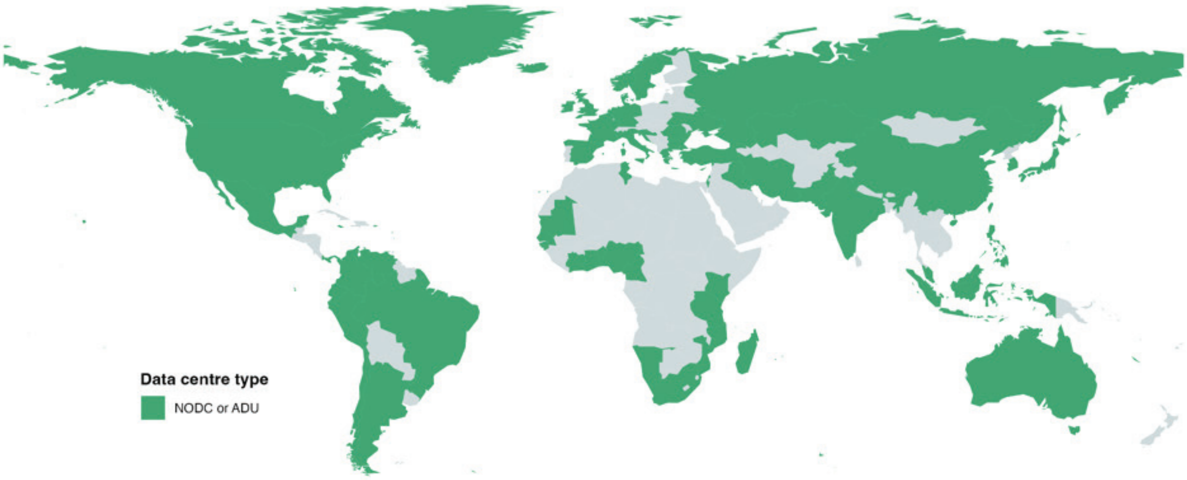

Figure 30. Map indicating countries, in which a NODC or ADU is placed (highlighted in green). Source: IOC-UNESCO.

in distributed resources including existing clearinghouse mechanisms. 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. An Ocean InfoHub Global Search portal has been developed as a demonstration of ODIS. The portal currently (December 2023) contains over 130,000 content items in 7 content categories: (i) Experts (27,000); (ii) Institutions (13,000); (iii) Documents (42,000); (iv) Training (1,500); (v) Vessels (113); (vi) Projects (3,600); and (vii) Datasets (48,000).

References

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UNESCO. 2021. UNESCO Recommendation on Open Science. Paris, UNESCO. https://doi.org/10.54677/MNMH8546

Additional resources

International Oceanographic Data and Information Exchangehttps://iode.org

Ocean InfoHub https://oceaninfohub.org

Ocean Data Information System https://oceaninfohub.org/odis

Ocean Biodiversity Information System https://obis.org

World Ocean Database http://wod.iode.org

The pivotal role of bathymetry in safeguarding the future of the planet

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Introduction

The Nippon Foundation-GEBCO Seabed 2030 Project – a collaborative project of the General Bathymetric Chart of the Oceans (GEBCO) and The Nippon Foundation – was launched in 2017 to act as a catalyst to the long-standing endeavour already underway to chart the ocean, spearheaded by GEBCO. Seabed 2030 seeks to mobilize the international community in support of this essential goal to be completed by 2030 and is primarily led by the following objectives: to incorporate all existing data into the publicly available GEBCO global grid; to identify areas for which no data exist and encourage and facilitate data collection in these areas so that we can map the gaps; to identify technology gaps in bathymetric mapping and encourage innovation in these areas; and to encourage and enable the acquisition of new bathymetric data from participating entities.

Description of findings, trends, status

GEBCO's grids continue to be made freely available for direct download or access through web map services. The current global grid interval is 15 arc-seconds, which is equivalent to grid cells of approximate size of 500 m x 500 m at the equator, although work is in progress to investigate making higher resolution data available – where it exists – for some areas. The grid is updated annually, typically in June, and the percentage of ocean floor mapped in the 2023 grid is just under a quarter (24.9%, Figures 31 and 32). This marks an increase of 5.4 million km2 of new data, equating to an area twice the size of Argentina, from the previous edition. Specific international, collaborative efforts have been underway for the polar regions (IBCAO and IBCSO) and the North Pacific.

In fact, since Seabed 2030's inception, a total of 90 million km2 of bathymetric data has been acquired, leading to consequential developments in scientific research, as

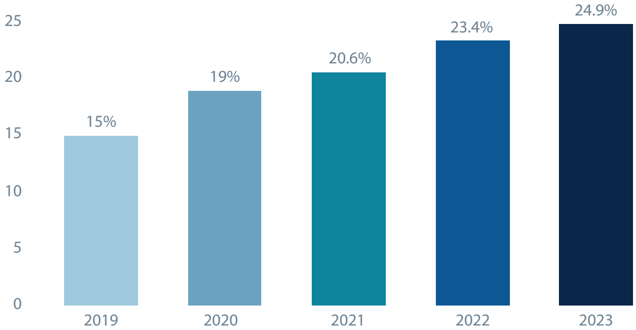

Figure 32. Percentage of seafloor mapped within the GEBCO grid per year. Source: Seabed 2030 Global Center and Stockholm University.

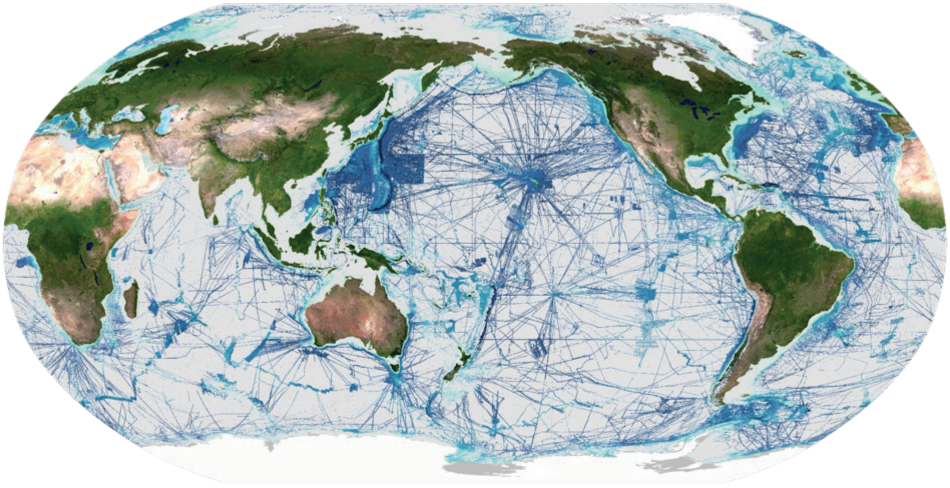

Figure 31. Map indicating countries, in which a NODC or ADU is placed (highlighted in green). Source: IOC-UNESCO.

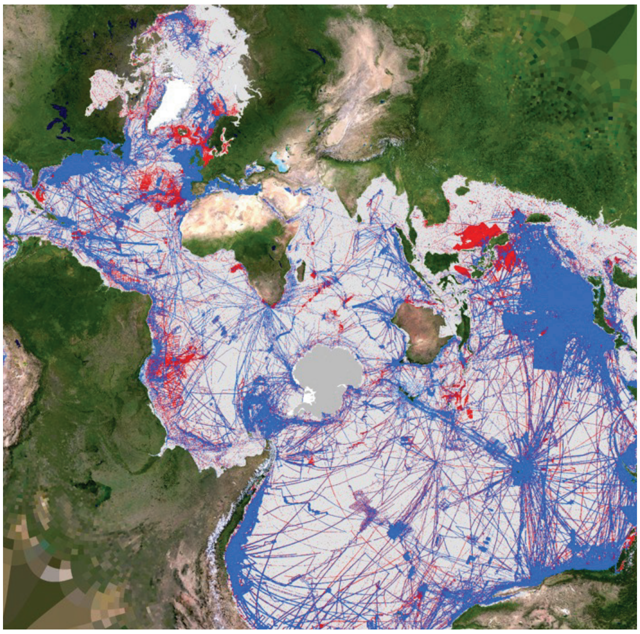

Figure 33. The blue areas show what regions are considered mapped in the 2021 GEBCO grid, and the areas in red show the increase coverage recorded in 2023. Source: Seabed 2030 Global Center

well as a range of discoveries.

Global bathymetry is now within reach by virtue of global partnerships, data mobilization and strides in technological innovation – including the deployment of uncrewed surface vehicles (USVs), which have transformed ocean mapping. But the task at hand is still considerable, with 75% of the ocean still to be mapped. While enormous progress has been made in the Arctic, including Greenland, in the last decade, considerable areas remain unmapped in the Antarctic, especially along the coastline of the continent. A portion of the ice sheet periphery particularly challenging to map are the ice shelf cavities around Antarctica and north Greenland, which require robotic technologies, in situ seismic surveys and ships with icebreaking capabilities (Figure 33). Despite the urgency of mapping these sectors to provide better scientific information to stakeholders about sea level rise, the community proceeds with traditional levels of funding, with very few cases of augmentation.

Mapping of the ocean floor is critical for ocean science and climate change research. Along the coastline of Greenland and Antarctica, bathymetry is critical to understand how ocean waters influence ice sheets and in turn how ice sheets melt to raise sea level. Without this knowledge, ice sheet models in charge of predicting sea level rise are fundamentally limited. Bathymetry is also fundamental to understand the cycling of heat and nutrients in the global oceans.

Mapping the ocean floor is a critical step towards informing decision-making in areas such as resource management, environmental change, and ocean conservation. It directly supports UN SDG 14: to conserve and sustainably use the ocean. Seabed 2030 is also a flagship programme of the Ocean Decade, which seeks to promote ocean science solutions to ensure the sustainable management of the ocean.

Conclusions and next steps

As we edge closer to the end of the decade, it is imperative that the global community comes together in support of this international endeavour – technological innovation is also pivotal to helping close the gap, not least as it enhances the efficiency and accuracy of data collection efforts, enabling researchers to overcome logistical challenges and reach previously inaccessible regions of the ocean floor. We need help and support to achieve our goal of complete ocean mapping by 2030, especially if we want to include polar regions. At present, while the efforts are ramping up, we must significantly increase pace to achieve that goal, and we need stronger support from the international communities, governments, industry, research programmes, and philanthropy.

Seabed 2030 now boasts over 50 partnerships with a range of organizations spanning the globe. As a new year gets underway – one which notably includes the Ocean Decade conference – we look forward to new and reinforced collaboration with governments, industry partners, research institutions and individuals alike to scale up data sources in support of this indispensable goal.

Additional resources:

https://seabed2030.org/

https://www.gebco.net/data_and_products/

An inspiring and engaging ocean where society understands and values the ocean in relation to human well-being and sustainable development

Status and trends in building global ocean literacy

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Introduction

The IOC Group of Experts on Ocean Literacy envisions a world where the ocean serves as a wellspring of inspiration and connection, where people universally appreciate and cherish the ocean's vital role in the well-being of humans, non-human others and the planet, as well as the courses of sustainable development to nurture this state of being. Achieving this vision requires all segments of society to acknowledge their profound ties to the ocean, developing a sense of care and connection, and fostering the necessary changes in values, behaviours and actions. The evolved notion of ocean literacy (McKinley *et al.*, 2023; Payne *et al.*, 2022) pivotal to the success of the UN Decade of Ocean Science for Sustainable Development (2021–2030), is gaining widespread recognition as a key focus for ocean action. It remains indispensable for the future sustainability of our ocean and the attainment of global goals in ocean management and conservation. Embracing ocean literacy is not just a goal; it is a shared commitment to safeguarding our global ocean for current generations and those yet to come.

Description of findings, trends, status

Since StOR 2022, processes to support national and global governments have been strengthened through the establishment of the IOC Ocean Literacy Group of Experts, which brings together an active team of researchers and practitioners representing 20 countries. This Group of Experts has identified key areas to support ongoing development of ocean literacy at global, national, regional and local levels: (1) education, (2) fund-raising, (3) support to policy-making and governance, (4) ocean literacy and climate change and other cross-cutting topics, and (5) communication which will be the core focus of their work in the coming years.

The StOR 2022 presented an overview on ocean literacy research production and the engagement in activities

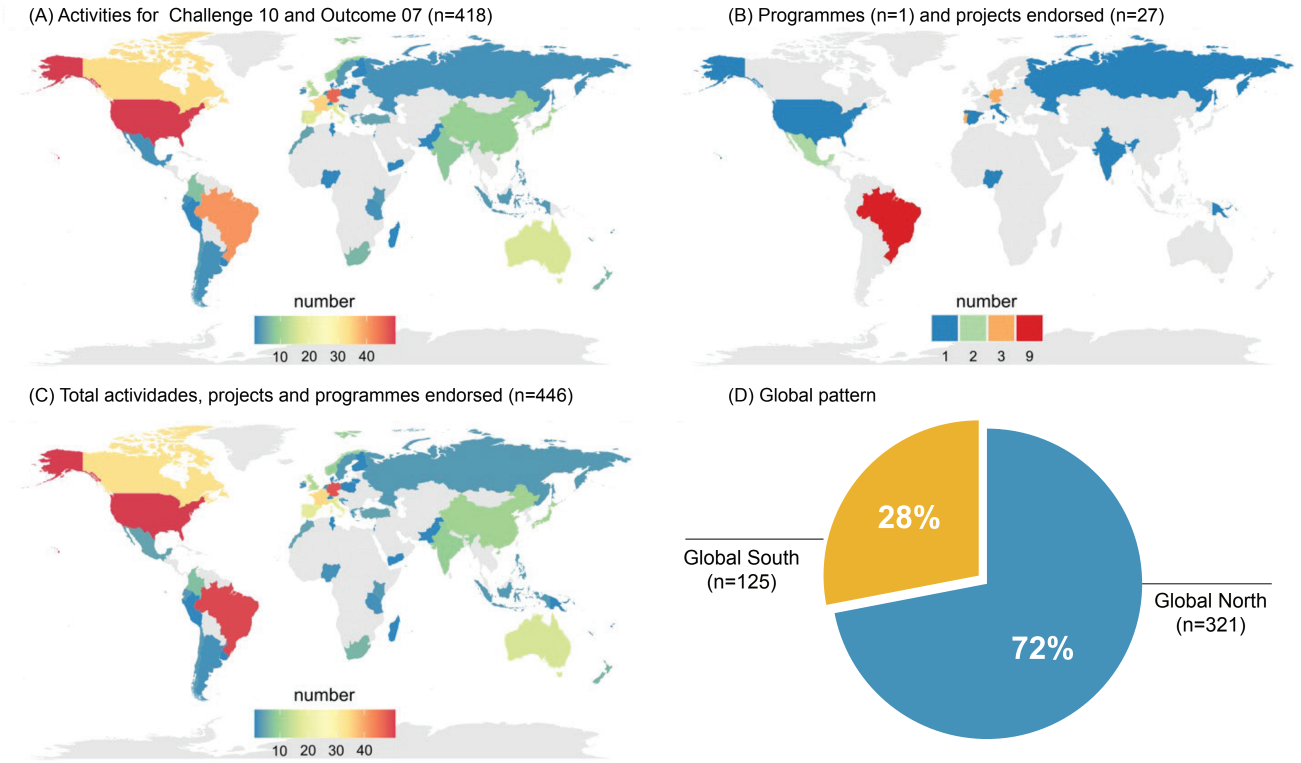

Figure 34 . Global distribution of the leader institutions of endorsed activities. Source: Authors compilation
Notes: Panel a. endorsed activities; panel b. projects and programmes in the UN Ocean Decade for Challenge 10 and Outcome 7 as of April 2024, including global pattern of the leader institutions for the total of 446 endorsed activities, projects and programmes (panel c.) and its distribution by Global North and South (panel d.).

from the Ocean Literacy Portal (IOC-UNESCO, 2022). Since then, there have been advances in ocean literacy-related research, engagement, networks, governance and decision-making, with ocean literacy continuing to be identified as key to address ocean sustainability and wider issues. Globally, 418 activities, 27 projects and the Ocean Literacy with All programme were endorsed by the UN Ocean Decade under Challenge 10 and Outcome 7 (Figure 34). Despite this momentum, there remains a need to strengthen regional and local strategies at all levels to foster and enhance ocean literacy, including increasing funding to support ocean literacy research, alongside programmes and engagement initiatives which support a truly global ocean literacy community. Importantly, such efforts must be intentionally designed to be inclusive of global perspectives and experiences. Currently, although Brazil is the lead country in endorsed projects (Figure 34, panel b.), highlighting the opportunity for Global South countries to contribute to the development, 72% of lead institutions in endorsed actions are from the Global North. More work is required to ensure the inclusion of essential perspectives and crucially leadership from institutions in the Global South (Figure 34, panel d.).

Over this same time period, events relating to ocean literacy have increased across a range of scales. Globally, a series of events ('Ocean Literacy Dialogues') were launched and they have engaged over 25,000 participants, with over 20 mentions in media reports and recordings of sessions from each edition made available online. There have been five editions to date:

- Portugal (organized by IOC-UNESCO as part of the UN Ocean Conference in June 2022)[16]
- Brazil (led by the Federal University of São Paulo with support of IOC-UNESCO in October 2022)[17]
- Canada (co-led by the Canadian Ocean Literacy Coalition and Marine Social Sciences Network, with support from IOC-UNESCO in February 2023)[18]
- Tanzania (led by IOC-UNESCO and UNESCO Dar es Salaam Field Office and the Sub Commission IOCAFRICA in November 2023)[19]
- Barcelona (led by IOC-UNESCO in partnership with a number of other organizations) as a two-day satellite

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16 See https://oceanliteracy.unesco.org/event/ocean-dialogues-united-nations-ocean-conference/.

17 See https://dialogosdaculturaoceanica.com.br/.

18 See https://oldialogues3rded.colcoalition.ca/.

19 See https://oceanliteracy.unesco.org/event/ocean-literacy-dialogues/.

event at the UN Ocean Decade Conference in April 2024[20]

In other global efforts, the Ocean Literacy Research Community (OLRC)21 continues to expand beyond its foundation in 2021 at the first Ocean Decade Laboratory, by addressing community-identified priority areas in globally relevant initiatives (e.g. the co-development of a global Ocean Literacy Survey22 to be piloted in 2024). Regionally, the growth and success of the All-Atlantic Blue Schools Network and the European Blue Schools Network has laid the foundation for an emerging global blue school network going forward. Indeed, these initiatives have been highlighted as examples of best practice, bringing local actions and engagement to the attention of heads of state and the wider ocean research and practice community. The Ocean Decade-endorsed Action Cultural Heritage Framework Programme from the Ocean Decade Heritage Network is working to ensure cultural and human perspectives are integrated into the Decade, with ocean literacy specific activities such as the Seavoice magazine highlighting diverse stories and experiences.23 Additionally, in the Gulf of Guinea, the African Youths Sustainable Ocean Campaign has been engaging younger generations in ocean issues. Across the world, art projects with individuals who are young and facing socio-economic challenges have been organized by the 'Artport-We are Ocean' initiative; while surfers, kite-surfers and other water sports enthusiasts have been engaged by the Surfstainable initiative. The Early Career Ocean Professional (ECOP) Programme has created Ocean Literacy hubs and focal points worldwide, empowering the new generation of leaders, while and the Asia Marine Educators Association (AMEA) launched a regional action plan to the ocean literacy development (AMEA, 2024).

These are a few examples of many initiatives where communities have been involved in ocean literacy discussions, from ocean literacy research to its role in wider marine conservation, climate change, blue economy, justice, equity and inclusion, communication and storytelling, culture and heritage, education and more. These discussions identified gaps and priorities, including the need to increase equity at regional levels and support ocean literacy narratives from the Global South. Work is needed to develop indicators and monitoring programmes to measure activity that impacts ocean literacy, to sustain initiatives that allow engagement over time, and uptake of best practices to afford ocean literacy outcomes (for more, see Glithero *et al.*, 2024). Moreover, the newly established IOC/UNESCO Subcommission of the Central Indian Ocean (IOCINDIO), along with other subcommissions, will be involved in several Ocean Decade Ocean Decade initiatives, including marine conservation, climate change adaptation, reducing coastal vulnerability, capacity-building and increasing ocean literacy.

The importance of ocean literacy within wider ocean governance discourse has continued to gain traction. Ocean literacy was identified as one of the priorities in the All-Atlantic Ocean Research and Innovation Alliance (AAORIA),24 in support of the development of effective policies and actions at national and regional levels. Many countries have established national ocean literacy expert groups (e.g. the Chilean National Oceanographic Committee–CONA); while in Africa, alongside existing efforts to embed ocean literacy techniques within Marine Spatial Planning and the wider Blue Economy agenda, an African Ocean Literacy Network has been proposed to convene different countries and sectors to support national and regional governance, aligning ocean literacy to local.

There has also been increased discussion of ocean literacy and communication in the UN Regular Process in the preparation of the World Ocean Assessment III to be launched in 2025. Additionally, there is a call for countries to include ocean literacy within school curriculums as a key aspect of Education for Sustainable Development by 2025, supported by the UNESCO Director-General, the IOC Executive Secretary and the UNSG's Special Envoy for the Ocean (IOC Circular Letter No 2951).

Conclusions and next steps

Ocean literacy practice and research is a strategic ally to optimize resources, accelerate behavioural change and improve the implementation of ocean conservation programmes and sustainability practices. While many advances have been identified since StOR 2022, so too have persistent gaps, that become particularly significant when considering the disparities between Global North–South regions. Policy and decision-makers play a significant role in maximizing the impact of ocean literacy initiatives and research. We present a range of areas where policy and decision-makers could focus their efforts and attention to ensure and maximize the impact of ocean literacy initiatives, practice and research:

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20 See https://oceanliteracy.unesco.org/event/ocean-literacy-dialogues-5th-edition-%f0%9f%93%8d-barcelona/.

21 Partners: Canadian Ocean Literacy Coalition; Dalhousie University; Universidade Federal de São Paulo (UNIFESP); Cardiff University; Marine Social Sciences Network; University of Connecticut/Connecticut Sea Grant; National Marine Educators Association; IOC/UNESCO Communications; Ocean Conservation Trust, UK; Simon Fraser University; Fundação GrupoBoticário.

22 See https://oceanliteracyresearch.com/.

23 See https://oceandecadechfp.org/.

24 See https://op.europa.eu/en/publication-detail/-/publication/dce41418-ec56-11ec-a534-01aa75ed71a1/language-en/format-PDF/source-259488329.

- Strengthen dialogue at global, national, regional and local levels between policy and decision-makers with the Group of Experts on Ocean Literacy to encourage alignment of decisions and actions from governments and decision-makers with ocean literacy and other cross-cutting priorities, including explicit consideration within SDG 14.
- Foster improved collaboration among global ocean literacy community and the wider ocean science communities to address the current inequitable access to ocean literacy resources.
- Seek nationally relevant ways to include ocean literacy in curricula and develop resources to support inclusion of ocean literacy in both formal and informal education.
- Mandate inclusion of traditional, local, place-based and Indigenous knowledge into ocean literacy resources and programmes, and wider ocean decision-making.
- Further develop opportunities and materials for training, professional development and knowledge exchange.
- Create mechanisms and programmes to guarantee financial support to ocean literacy actions and research at national and local levels.
- Increase diversity, equity and inclusion in ocean literacy initiatives and research at national, regional and local all levels.
- Integrate ocean literacy priorities in synergy with the outputs of the Challenge 10 Working Group.

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Involving civil society and the private sector in the Global Ocean Observing System

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[1] World Meteorological Organization
[2] Intergovernmental Oceanographic Commission of UNESCO

Introduction

Understanding and predicting ocean changes is the foundation for guiding effective mitigation and adaptation strategies, and it requires continuous and comprehensive global-scale oceanographic and meteorological observations.

Recognizing the high potential of citizens, sailors, mariners and businesses collecting and sharing more ocean data, the Global Ocean Observing System (GOOS) is actively collaborating with various projects and programmes on the further inclusion of non-scientific stakeholders in the field of ocean observations. The Ocean Decade Odyssey Project as well as the Dialogues with Industry action exemplify this endeavour by working with new communities towards an expanded ocean observing system that can deliver the ocean data society will need tomorrow (Rusciano *et al.* 2022; Willis *et al.* 2024).

Other efforts are also underway within the framework of the Ocean Decade. Under the leadership of the Corporate Data Group, strategies and guidelines are being established for companies in marine sectors to publicly share their privately owned met-ocean data, benefiting science and society at large.

Finally, in recent years, new private sector providers of ocean data have entered the ocean observing 'marketplace', offering observations and model output through different business models, and new networks have developed that take advantage of existing private sector infrastructure.

All these different approaches are seeking to expand ocean observing capacity and have different costs and benefits.

Description of findings, trends, status

In a time of constrained resources for academic cruises and national research programmes, broader community engagement and support offers a promising avenue for complementing and expanding ocean observation efforts. Leveraging the expertise and resources of private companies can enhance data collection and analysis, key for thriving blue economies and sustainable development.

Collaboration with private partners has its historical roots in the Voluntary Observing Ship Scheme, the oldest ocean observing network, first developed almost 150 years ago. For over a century, merchant vessels have played a pivotal role in routinely sharing marine data. Presently, approximately 2,000 vessels, mainly from the shipping industry, actively participate in ocean observation efforts. The ambition is to have the global fleet, including container ships, fishing and leisure vessels, equipped with met-ocean sensors to exponentially increase ocean observations. In this regard, discussions with industry leaders about returns on investment are essential, including improved weather forecasts, reduced energy consumption, optimized routing and contributions to environmental initiatives.

Over the past decade, GOOS – through its operational centre OceanOPS – has also established partnerships with other diverse mariners, including the sailing community, and has been equipping race vessels with oceanographic and weather sensors. These collaborations offer unique opportunities to collect ocean observations and deploy instruments in under-sampled regions, like the Southern Ocean (Figure 35). To operationalize and standardize these useful partnerships and to ensure a robust data processing chain, OceanOPS launched the Odyssey Project, endorsed as an Ocean Decade project in 2021. In addition, there are a number of national initiatives advancing the citizen science concept to support ocean observation, emphasizing the need for coordination of initiatives and data flows.

Building on UN Ocean Decade momentum, recent efforts by the Corporate Data Group have identified several private companies willing to share their data publicly. For instance, companies involved in the Ocean Decade Corporate Data Group already contribute valuable bathymetry data through the Nippon Foundation/GEBCO Seabed 2030 programme. However, there is a clear need for specific resources and expertise to process crowd-sourced data according to global standards, and to assess the value of such data to ocean models and data services.

The groundbreaking Ocean Decade 'Dialogues with Industry' action co-led by GOOS, with the Marine Technology Society and the National Ocean and

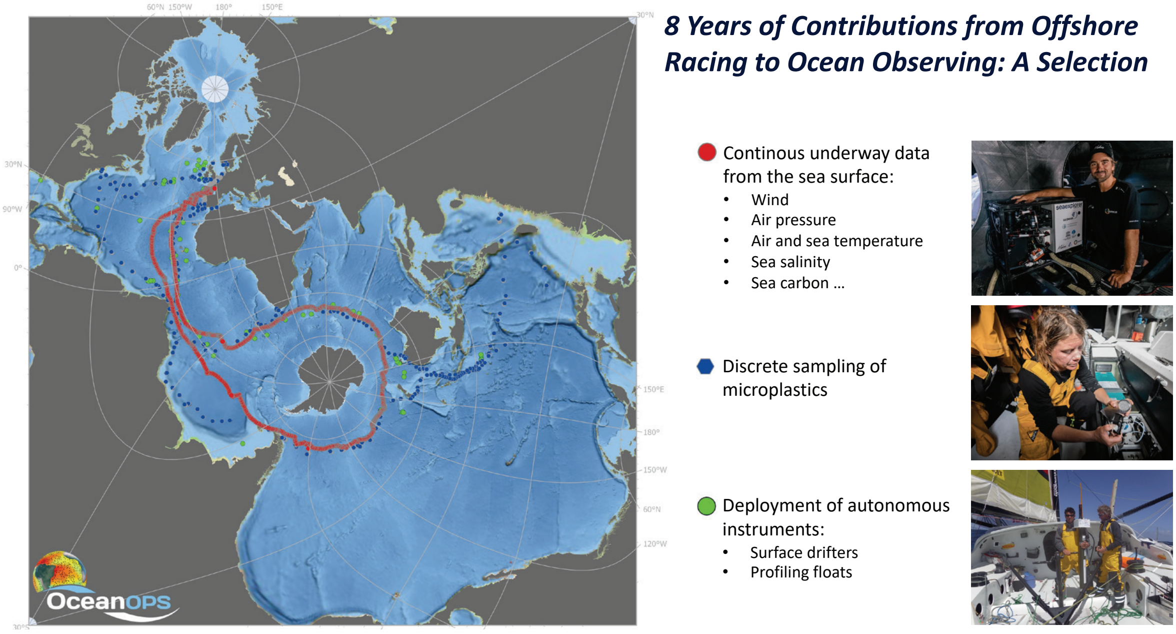

Figure 35. A selection of eight years' contributions to ocean science and observations from ocean sailors. *Source*: OceanOPS.

Atmospheric Administration (NOAA), and including industry representatives, also works on new pathways for industry and the public sector to collaborate in solving key issues that inhibit the development of an expanded ocean-observing system and a mature Ocean Enterprise. The Dialogues with Industry Roadmap identifies the priority pathways for action resulting from this collaborative work (Willis *et al.*, 2024).

The Roadmap identifies 26 high-priority action pathways across three key areas: Improving the Marketplace, Collaboration for Societal/Governmental Change and Shaping the Future. All stakeholders in the Ocean Enterprise, spanning public, private and academic sectors, are invited to join forces in accelerating the Roadmap's implementation. Financial support from NOAA under the Inflation Reduction Act will support this effort in future years, and the emphasis will be on accelerating actions identified through the Dialogues with Industry (Willis *et al.*, 2024).

Conclusions and next steps

The ocean is vast and ocean observations and data are still scarce to support decision-making, protect lives and build sustainable blue economies. There will not be a global and sustained ocean observing system without non-academic partners. Innovative collaborations with civil society and private sector hold significant potential for advancing real-time ocean observation and stewardship. These new partnerships and activities were further strengthened during the COVID-19 pandemic, as restrictions impacted the deployment of oceanographic instruments and data collection by research vessels.

Today, more partnerships and initiatives are being developed to spread and operationalize met-ocean observations from merchant ships, fishing fleets and other marine operators or ship users from the coast to the open ocean, and yet their full potential is still to be unleashed.

Unlocking this vast potential will need dedicated resources for coordination, integration and data production. The UN Ocean Decade offers a unique framework to support and amplify these non-academic contributions to the GOOS.

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Additional resources

Ocean Decade Corporate Data Group https://oceandecade.org/ocean-decade-corporate-data-group/

Ocean Decade Odyssey Project https://oceandecade.org/actions/ocean-decade-odyssey/

Ocean Enterprise https://mtsociety.memberclicks.net/ocean-enterprise-initiative

Seabed 2030 https://seabed2030.org/

Progress to include Indigenous and traditional knowledge in ocean science

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[1] United Nations Educational, Scientific and Cultural Organization

Introduction

There are diverse Indigenous peoples using, conserving and knowing the ocean and its resources. These include peoples living at different latitudes, from the Arctic to the tropics, from coastal and island communities to those who are transhumant or voyaging on the ocean. These peoples observe the state of the ocean on a daily basis, and often reflect on the intricate balance between nature and humanity. The ocean is a vital source of sustenance, culture and connectivity. Indigenous knowledge includes both technical knowledge and cultural relationships with the ocean and marine species. The ocean is described as a living system that sustains diverse resources and human communities alike. Indigenous knowledge systems are under threat due to tenure insecurity, climate changes, pollution, contamination and overfishing, which disrupt marine life and traditional practices that depend on it. Indigenous peoples advocate for a sustainable approach to ocean management and governance of their territories, while prioritizing intergenerational stewardship.

Description of findings, trends, status

Indigenous peoples have a multifaceted relationship with the marine environment which extends beyond utilitarian aspects of resource usage, to encompass spatial, spiritual, cultural, and ancestral dimensions. For Indigenous communities, the ocean is not merely a resource but is a place of practices, livelihoods, neighbourliness, culture and identity. For some peoples, the ocean has sacred and spiritual dimensions including hosting deities, sacred sites, ancestors, and spirit beings. This multifaceted relationship with the ocean guides their practices, from detailed marine observation to sustainable fishing and conserving marine habitats, to regular or intermittent sailing and voyaging. The sum of these relationships, highly diverse across the planet, means that Indigenous Peoples have sophisticated knowledge of many aspects of the ocean, including its biodiversity trends, climate-related changes, physical shape and movements, and challenges to marine species and associated livelihoods.

The knowledge and governance of Indigenous peoples highlights the ocean's role in influencing life on land, on the cryosphere and in the tropical marine zones. Likewise, Indigenous peoples have valuable knowledge about how human behaviour on land is shaping the ocean environment, including the impacts of tourism infrastructure, sewerage, blocking of rivers and other drivers of change of hydrological cycles that connect source to sea. They have observed first-hand the changes in sea levels, the warming of waters and shifts in marine biodiversity, attributing these trends to broader environmental neglect and exploitation. Their traditional ecological knowledge offers invaluable insights into natural cycles and can complement scientific research, providing a more comprehensive understanding of marine ecosystems' health and resilience.

Indigenous voices call for inclusive governance frameworks that recognize their rights and knowledge, advocating for participatory approaches in marine conservation and management policies. This is particularly pertinent with the new Marine Protected Areas targets under the Kunming-Montreal Global Biodiversity Framework (30 x 30). They emphasize the importance of protecting intergenerational knowledge transmission and cultural systems, as well as sacred or tabu sites, supporting sustainable livelihoods, and restoring the health of marine ecosystems through practices that align with their cultural values and environmental ethics.

However, the challenges Indigenous peoples face are multifaceted, including legal battles over territorial waters, the impact of industrial activities on marine life and the broader effects of global climate change. Despite these hurdles, Indigenous peoples remain at the forefront of efforts to advocate for sustainable ocean practices, embodying a commitment to stewardship that is vital for the well-being of our planet (Proulx *et al.*, 2021). The recent adoption and ratification of the High Seas Treaty on biodiversity beyond national jurisdiction (BBNJ), which includes reference to traditional knowledge systems, opens a new frontier for Indigenous peoples to engage with the United Nations on marine biodiversity and connectivity.

The examples below underscore the vital and increasing contributions of Indigenous peoples to marine conservation, highlighting their observations on the status of the ocean and the importance of including their knowledge and practices with global efforts to sustain its health.

Figure 36. Urak Lawoi women fishing in Thailand. Source: Shin Sirachai

1. Australia (The Great Sandy Biosphere Reserve) (Hockings *et al.*, 2019)
2. Cabo Verde (Maio and Fogo Biosphere Reserves) (Rochette *et al.*, 2021)
3. Canada: the Qikiqtani Inuit and Ice-edge Ecosystems (Steiner *et al.*, 2021)
4. Colombia (Tribugá-Cupica-Baudó, Ciénaga Grande de Santa Marta, Belt, El Tuparro, Seaflower and Sierra Nevada Santa Marta biosphere reserves) (Chavez *et al.*, 2021)
5. Maldives (Baa Atoll and the Addu Atoll (known also as Seenu Atoll) biosphere reserves). (UNESCO, 2022)
6. Martinique Biosphere Reserve[25]
7. New Zealand: the Māori concept of 'Kaitiakitanga' (New Zealand National Commission for UNESCO, 2024; O'Callaghan *et al.*, 2019; Roberts *et al.*, 1995)
8. Thailand: Surin Islands National Marine Park and the Moken, Tarutao National Marine Park and the Urak Lawoi (UNESCO, 2007; Figure 36)

Conclusion, next steps

Indigenous peoples' observation of the marine environment has been largely ignored in scientific research and policy-making. There are signs that traditional marine knowledge is being revitalized, including in long-distance traditional voyaging in the Pacific. Indigenous peoples as holders of rights, knowledge and active marine custodians are key partners for the United Nations. Indigenous peoples' value systems can help inspire new understanding of the ocean, sustainable livelihoods, climate responsiveness and effective conservation action. Indigenous peoples are also important advocates for the use of multiple knowledge systems, multiple evidence-based approaches to environmental management, governance and policy-making. Indigenous peoples also bridge the administrative and conceptual disconnect between land and sea, which is central to systemic approaches to understanding the interaction of ecosystems and human behaviour.

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State of the Ocean Report 2024

The State of the Ocean Report has the ambition to inform policymakers about the state of the ocean and to stimulate research and policy actions towards 'the ocean we need for the future we want', contributing to the 2030 Agenda and in particular SDG 14, as well as other global processes such as the UNFCCC, the Convention on Biological Diversity and the Sendai Framework for Disaster Risk Reduction.

Structured around the seven UN Decade of Ocean Science for Sustainable Development Outcomes, the Report provides important information about the achievement of the UN Ocean Decade objectives and, in the longer term, about ocean well-being.

More than 100 authors from 28 countries contributed to the Report. The different sections provide insights on ocean-related scientific activities and analyses describing the current and future state of the ocean, addressing physical, chemical, ecological, socio-economic and governance aspects.

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

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