

Section 4

Chapter 2

Scientific understanding

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Key points

- The ocean is a single and complex interconnected system, the planet’s “life support system”, combining biological, physical and chemical processes while interacting with the atmosphere. It hosts millions of species, many still unknown.
- Managing human impacts on the ocean is essential for preserving life on Earth, including humankind. Despite advancements, significant challenges persist, necessitating ongoing improvements to ensure long-term sustainability.

1. Introduction

A comprehensive scientific understanding of the ocean and its complex functioning (Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO), 2020) is essential for assessing human-induced impacts.

Evidence-based science underpins this effort, integrating disciplines, including marine biology, ecology, ethology, physical and biological oceanography, climatology, geology, marine chemistry, genetics, acoustics, economics, sociology, ocean literacy and traditional knowledge.

An integrated multidisciplinary approach addresses societal challenges, improves the understanding of oceanic complexities, identifies knowledge gaps, enhances sustainable uses, preserves spiritual values and ecosystem services and supports Sustainable Development Goal 14. Advances since the publication of the second *World Ocean Assessment* are detailed in each chapter of the third *Assessment*.

Nonetheless, the ocean is increasingly threatened by acidification, warming (see sect. 4, chap. 3), eutrophication (see sect. 4, chap. 3), plastics pollution (see sect. 4, chap. 6), deep-sea mining (see subsect. 5A, chap. 7) and anthropogenic noise (see sect. 4, chap. 6). Persistent organic pollutants (POPs, see sect. 4, chap. 6), heavy metals and radioisotopes (see sect. 4, chap. 6) from human activities, along with overfishing and illegal, unreported and unregulated (IUU) fisheries (see sect. 4, chap. 1; subsect. 5A, subchap. 1A; and subsect. 5B, chap. 5), remain critical issues.

A significant milestone was the adoption in 2023 of the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction following two decades of negotiations. This marks significant progress towards better ocean management.

Improving scientific knowledge is essential for enforcing the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction and advancing Sustainable Development Goal 14.

2. Advances in data, theories, technology and models, including enhancing socioeconomic understanding

The symposium organized in 2023¹ by the Division for Ocean Affairs and the Law of the Sea of the Office of Legal Affairs of the United Nations, in collaboration with IOC-UNESCO, and multidimensional indications (Boero and others, 2019a, 2019b; Qiao, 2024; IOC-UNESCO, 2024) provided an opportunity for useful science-policy discussions, supporting enhancements to the Sustainable Development Goals, particularly Goal 14.

Advancements since the second *World Ocean Assessment* include:

- The Intergovernmental Panel on Climate Change (IPCC, 2023) improved data, forecasts and ocean understanding.
- Technological improvements boosted knowledge of ocean health, climate processes and the complex ocean ecosystem, as follows:
 - Combining in situ data with satellite remote-sensing assimilation technology has produced a consistent global meteorological data set since 1958, improving physical oceanography (European Centre for Medium-Range Weather Forecasts, 2024; National Oceanic and Atmospheric Administration (NOAA)² (see also subsect. 5A, chap. 6).
 - Drones improve real-time data collection (Fillingham and others, 2023) (see also sect. 4, subchap. 5G; and subsect. 5A, chap. 2, subchap. 3B and chap. 9).
 - Artificial intelligence progressively improves prediction capacity, although integrating partial artificial intelligence models into existing broader numerical models remains challenging (Ebel and others, 2024). Improving data-sharing remains essential.
 - Marine microbiome studies in the most remote areas and assessments of ecosystem health are now possible using new sequencing technologies and environmental DNA (Haddock and Choy, 2024) (see also subsect. 5A, chap. 5).
 - Ocean warming is evident not only at the surface but also at depths below 2,000 m globally (Cheng and others, 2024; Johnson and Purkey, 2024).
- Improved taxonomical, genetic and ecological studies have expanded knowledge of deep-sea biodiversity. Newly identified species include 33 species of cephalopods, 7,252 species of invertebrates and 3,502 species of fishes (see sect. 4, chap. 5 and subchaps. 4B, 4C and 4D).
- Conservation status has improved for, among others:

¹ See www.un.org/regularprocess/sites/www.un.org.regularprocess/files/summary_of_discussions_symposium_final_for_circulation.pdf.

² See www.star.nesdis.noaa.gov/data/star_docs/meetings/2018JPSSAnnual/Thursday/5_0_Garrett_LunctimeBB_DataFusion_v2.pdf.

- Eastern Atlantic bluefin tuna (International Commission for the Conservation of Atlantic Tuna (ICCAT), 2022)
- Southern bluefin tuna (Commission for the Conservation of Southern Bluefin Tuna (CCSBT), 2023; International Seafood Sustainability Foundation (ISSF), 2025)
- Four subpopulations of loggerhead turtles (International Union for the Conservation of Nature (IUCN), 2023)
- Mediterranean monk seal (Valsecchi, 2024).
- Management tools and initiatives have improved, including advancements in marine spatial planning (see sects. 1 and 3). Efforts to decarbonize shipping (Anonymous, 2023a) and reduce underwater noise and other ecological impacts are advancing (Marine Environment Protection Committee (MEPC), 2023; Shuye and Lidong, 2024).
- Socioeconomic studies have improved for shipping, fisheries, marine aquaculture, oil extraction, coastal activities and deep-sea mining (Benites and others, 2023; de Matos and others, 2023; Bin Hassan and others, 2024).

Policy and international activities include:

- The European Union mission “Restore our Ocean and Waters” (2020) initiated hundreds of new projects, including the European Digital Twin of the Ocean, marking a significant step towards sustainable ocean management (Könnölä and others, 2021). By combining real-time data, artificial intelligence models and simulations, digital twins of the ocean create virtual representations of the ocean that can support better decision-making and ocean governance.
- The United Nations General Assembly (UNGA) (2024) highlighted the importance of well-structured marine geospatial information management infrastructure for sustainable ocean development.³

3. Key region-specific changes

Arctic Ocean

The Arctic Council monitors climate change impacts, including sea level rise, altered density in the Northern Atlantic and a slowing Gulf Stream (Piecuch and Beal, 2023). These changes drive species, including pathogens, from the Pacific into the Arctic and the Atlantic. Ice melt has also opened new shipping routes, raising pollution risks, with significant environmental, social and economic implications.

North Atlantic Ocean, Baltic Sea and North Sea

The Commission for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Commission) (Anonymous, 2023b) updated the status of the North-East Atlantic, noting improvements since the publication of the second *World Ocean Assessment*, such as a decrease in concentrations of POPs. However, concerns remain, including ocean acidification, noise pollution and the declining status of marine birds (see sect. 4, subchap. 4G). Climate change is probably the greatest pressure affecting

³ See www.un.org/Depts/los/doalos_publications/publicationtexts/MarineGeospatialInfoMgmt.pdf.

plankton (see sect. 4, subchap. 4A) and endangers coastal and benthic habitats. Protection of the Sargasso Sea⁴ is advancing (Mackey, 2021; Roe and others, 2022).

The Baltic Sea assessment (Baltic Marine Environment Protection Commission (HELCOM), 2023) showed that climate change increases risks of biodiversity loss and aggravates the impact of existing pressures.

Mediterranean Sea and Black Sea

The Mediterranean Sea and the Black Sea host rich biodiversity but face growing pressures. Climate change and shipping drive increasing numbers of immigrant species (Galanidi and others, 2023), threatening local biodiversity and complicating management efforts. Studies are now focused on oceanographic changes and their effects on the distribution of fish species (Di Natale, 2024). Ongoing conflicts in the Black Sea hinder assessments.

South Atlantic Ocean and the wider Caribbean

Recent studies highlight climate change impacts on the Brazil Current, including altered heat transport, upper ocean salinity shifts, deep ocean freshening and intensification, and the polewards shift of the Brazil Current, which contribute to ecosystem changes (Franco and others, 2020; Chidichimo and others, 2023).

Rising surface temperatures in the Caribbean Sea have increased hurricane frequency and intensity, threatening endangered corals and reefs (Hernández-Delgado and others, 2024) and boosting mass blooms and stranding of pelagic *Sargassum* species (Robledo and others, 2021).

Along the Brazilian continental margin, new seafloor morphologies and habitats have been discovered, including carbonate constructions, siliciclastic drifts and multiple submarine canyon systems (Steinmann and others, 2020; Alves and others, 2023; Jovane and others, 2024; Tagliaro and others, 2024). Challenges persist in controlling invasive species, offshore salmon farming and fisheries for shrimps and squids (Seto and others, 2023; de Carvalho-Souza and others, 2024).

Understanding of the ocean system in the Gulf of Guinea has improved (De Esteban and others, 2023).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

An anticyclonic gyre in the central Indian Ocean induces the downwelling of nutrients, reducing productivity and mesopelagic organisms (Jena and others, 2013; Cherel and others, 2020). The Agulhas Current generates highly productive mesoscale eddies between Madagascar and Africa (Annasawmy and others, 2018; Vianello and others, 2020). The Indonesian Throughflow has been reassessed (Fritz and others, 2023).

International research surveys have improved understanding of pelagic diversity, distribution, migration and trophic and biophysical interactions, as well as the impact of warming temperatures (Ternon and others, 2014; Annasawmy and others, 2020a, 2020b, 2022a, 2022b, 2024a, 2024b, 2025). Indian Ocean warming extends to 750 m in depth, with deep cooling observed in the subtropics (Wenegrat and others,

⁴ Mostly promoted by the Sargasso Sea Commission and various non-governmental organizations.

2022). Plastic pollution remains an important threat (Woodall and others, 2015; Fůrychov and others, 2024).

North Pacific Ocean

The North Pacific Marine Science Organization improved model approaches, using multidisciplinary components (Lew and others, 2024). Ecosystem assessment methods (Hunsicker and others, 2022; Kobari and others, 2022) have been reviewed to enhance tools and capacity-building, improving future regional understanding of the ocean. Prediction models for large pelagic species have been included to cover long-term predictions in different environmental scenarios (Muhling and Chen, 2020).

The China Ocean Agenda 21 has incorporated the 2030 Agenda for Sustainable Development in order to promote marine protection. In 2023, the Marine Environmental Protection Law was improved to integrate land-sea management (Information Office of the State Council, 2024).

Tropical (central) Pacific Ocean

This area is a major biodiversity hotspot, but also an area strongly affected by climate change.

Many of the coral reefs in this region, such as in the Cook Islands and the Great Barrier Reef, face repeated bleaching (Henley and others, 2024). The vaquita (*Phocoena sinus*), a critically endangered porpoise, continues to approach extinction in Baja California (Rojas-Bracho and Taylor, 2021; International Whaling Commission (IWC), 2023).

El Nio and La Nia complicate the understanding of climate change, affecting species distribution, especially for tunas. The combined effects have environmental, economic and social impacts. New long-term models (Barrier and others, 2023) aid their management, using updated scientific understanding.

Marine litter and rising sea levels are increasingly threatening islands and communities.

The Association of Southeast Asian Nations (ASEAN) (Anonymous, 2025) is developing new initiatives to facilitate the inclusive use, management and conservation of oceanic resources and cooperation in the marine sector.

South Pacific Ocean

Pollution from many sources, climate change and El Nio are worsening marine environments (Atalah and Sanchez-Jerez, 2020). Concerns remain over regional and high-seas fishery management (Food and Agriculture Organization of the United Nations (FAO), 2024) and increasing deep-sea mining (Schofield, 2018). Plastic pollution and its impact on marine life are increasing (Muoz-Perez and others, 2023; Savoca and others, 2021). Oceanographic modelling is improving (e.g. fishmip.org).

Southern Ocean

This remote region is difficult to study (Antonello, 2018; Howitt, 2024). Understanding is advancing through active and passive ocean observation and modelling (Gray, 2024). Ocean circulation, which is crucial to global processes, and the carbon cycle are driven by complex interactions of ice, sea level and oceanic processes across wide spatial and temporal scales (Bennett and others, 2024; Gray 2024; de Souza and Morrison, 2024). Sea ice is a key component of the ecological web in this region (Swadling and others, 2023) (see sect. 4, subchap. 5K).

4. Outlook for scientific understanding of the ocean

Due to the ocean's size and complexity, understanding of its functions and the human impacts on it, although progressing, remains limited. The discovery of "dark oxygen" in 2024 suggests many more secrets that are currently unknown (Sweetman and others, 2024).

Climate change tipping points, such as phase change in the Labrador Sea, the subpolar gyre and/or the Atlantic Meridional Overturning Circulation, require further study. Understanding of cumulative impacts will benefit from a mainstream approach, for example by adopting a four-dimensional ocean approach (latitude, longitude, depth and time). The complexity of marine biodiversity, including microbial communities, is much broader and complex than is currently understood.

Autonomous and biomimetic underwater vehicles, autonomous surface vehicles and uncrewed surface vehicles are revolutionizing high-resolution marine data collection. Sailing vessels opportunistically collect marine data and water samples during oceanic races in remote areas.

Advanced modelling and artificial intelligence are enhancing scientific understanding of the ocean. Environmentally driven prediction models for large pelagic fish reveal large-scale oceanic changes (Petrik and others, 2020).

New analytical techniques improve knowledge of the distribution, role and pathological effects of nanoplastics for marine life and humans (Catarino and others, 2022; Zaki and Aris, 2022; Chaoli and others, 2024).

Improved seafloor mapping, a flagship programme of the United Nations Decade of Ocean Science for Sustainable Development (Seabed 2030, 2025), advances understanding of benthic and deep environments for management and conservation.

A key emerging challenge is the underwater noise impacts of fixed and floating offshore wind farms on migratory pelagic species (Hendon and others, 2024).

Gradual warming increases risks for Indigenous Peoples and coastal communities (IPCC, 2023). Cross-disciplinary and trans-disciplinary studies could improve by being expanded to support informed decisions integrating biological, environmental, social and economic approaches for a sustainable ocean, providing a more holistic approach to Sustainable Development Goal 14.

5. Key remaining knowledge gaps

Despite the ocean's importance, Sustainable Development Goal 14 remains the least funded of all the Goals (Conrad and others, 2022), affecting oceanic research. Key gaps were identified by IOC-UNESCO (2024) and the third *World Ocean Assessment*:

- Seafloor mapping remains limited to 27.3% (Seabed 2030, 2025).
- Little of the vulnerability of marine biodiversity, species genetics and microbial communities, particularly in the deep sea, to [climate change and emerging economic activities](#) is understood.
- Understanding of microbial diversity and its role and function in biogeochemical processes is still very limited.

- There are faster climate change impacts on ocean circulation and cumulative effects on the ocean-atmosphere interface and on marine communities and species, including population dynamics.
- Marine and coastal ecosystem-based management can be supported by scaling up collaboration and data collection to address multiple stressors.
- Research output from the global South is often underrepresented, as there is reduced capacity-building relative to the global North.
- Understanding of POPs and emerging unregulated pollutants, along with cumulative health effects on living species, is still limited.
- Understanding of underwater anthropogenic noise impacts on marine species and migrations is very limited.
- Knowledge of chemical and biological processes of polymetallic seafloor deposits is poor.
- Understanding of plastics and nanoplastics dynamics in the ocean and their biological effects is extremely poor.
- Sustainable ocean plans require stronger evidence-based decision-making and national oceanic accounting systems.
- Climate-resilient oceanic economy projects need better conservation and socioeconomic integration for local communities.
- Scaling up climate mitigation, including renewable energy and coastal ecosystem management, is essential.
- Marine carbon dioxide (CO₂) removal feasibility, impacts and policies require urgent study.
- Risk assessment tools for coastal communities and marine industries need development.
- Investment in ocean science and digital representation requires new financial models.
- Greater effort is needed to preserve and catalogue Indigenous, traditional owner and local community knowledge.
- A large but unknown proportion of historical scientific information is not yet available digitally and remains inaccessible to those who need the information.
- Regional fishery management organizations (RFMOs) are working on improving the integration of multidisciplinary ocean management and climate change in their approach through outreach to their contracting parties.

6. Key remaining capacity gaps

Sectoral gender gaps are decreasing, but persist in some areas (see subsect. 5B, chap. 6). Regional capacity gaps remain (Potter and Pearson, 2023). Partnerships and cooperation are transversal tools for improving capacities.

Uniformity in infrastructure distribution needs improvement, including specialized multidisciplinary scientific capacity, remote sensing tools, modern oceanographic instruments, autonomous vessels, research ships and modern land-based support laboratories. Ocean data would benefit from increased or improved calibration with in situ measurements. Despite advances in modelling and forecasting, capacity gaps between advanced and developing economies remain significant. Artificial intelligence might help.

Gaps in biodiversity knowledge persist due to declining taxonomic expertise (Boero, 2001; Löbl and others, 2023) and the underutilization of international funding (Boero, 2010), limiting marine biodiversity research.

Several capacity gaps in ocean science were identified under the United Nations Decade of Ocean Science for Sustainable Development (Arbic and others, 2024), including: language barriers, underrepresentation of marginalized groups (women, persons with special needs, early career professionals, Indigenous Peoples, etc.) and limited data accessibility. A more open data-sharing system can reduce capacity gaps. The Decade coordination office for ocean data-sharing is a crucial tool for collaboration and improving access to ocean science data (Anonymous, 2023c).

7. Emerging issues

Recovery of existing scientific knowledge

Scientific and cultural ocean knowledge, gathered over centuries, is scattered across thousands of documents around the world, which are often unavailable digitally. This knowledge is crucial for understanding marine environment evolution and the historic exploitation of ocean resources (Niner and others, 2024), but is often not available digitally. While some organizations, such as Google, the Digitisation Centre of Western Australia and the Digital Public Library of America, are making efforts to recover and publish such information, ensuring its accessibility (Kaspar and others, 2015; Di Natale, 2022), there is still a large amount of information that is not accessible. Although limited to information from the most recent decade, improving the ocean literacy programme under the United Nations Decade of Ocean Science for Sustainable Development will also assist with this process.

Indigenous Peoples and local coastal community knowledge

Coastal, island and Indigenous Peoples communities hold ancient cultural knowledge about the ocean, including on marine species, seasonality and natural phenomena (Vierros and others, 2020; Pardie and Champion, 2022; Strand and others, 2022) (see sect. 5, particularly subsect. 5A, chap. 7, and subsect. 5B, chaps. 2 and 8). Traditional boat-building techniques and marine gear design are derived from the ancient experiences of global coastal communities. This precious knowledge is at risk of disappearing if not urgently recovered for future generations and for current management (Kaiser and others, 2019). Ethno-anthropologists are essential in this effort. Preserving this knowledge not only safeguards history but also supports future marine research, providing essential baselines for long-term environmental assessments and policy development.

A new paradigm: ocean rights

The principles of ocean rights were presented to the General Assembly in 2023 after extensive international discussions. A legal paradigm shift is needed to ensure the adoption of the Universal

Declaration of Ocean Rights by 2030,⁵ safeguarding the planet’s “life support system”. While not formally endorsed, this innovative approach will provide a comprehensive legal framework for United Nations bodies and stakeholders, aligned with existing universal declarations (Bennett and others, 2024).

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⁵ See www.earthlawcenter.org/ocean-rights and www.theoceanrace.com/en/ocean-rights.

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