Section 1

Overall summary

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Key points

- The sustainable use of marine resources and services underpins environmental integrity, economic resilience and social stability, with the ocean playing a central role in regulating climate, maintaining biodiversity and providing food, minerals and energy vital to human well-being.
- However, the ocean is under mounting stress from overexploitation, pollution and the accelerating impacts of climate change, while global demand for biological, mineral and energy resources continues to grow.

1. Introduction

The ocean covers more than 70% of the planet and is the largest and most interconnected ecosystem. It serves as the planet’s primary life-support system and contains the majority of Earth's biodiversity. The ocean plays a crucial role in global nutrient cycles, particularly the carbon and nitrogen cycles, and is a major producer of oxygen.

The ocean plays a fundamental role in the evolution of climate change as part of the planet’s climatic system. The ocean has already absorbed over 90% of the excess heat and 30% of the carbon dioxide (CO_2) released into the atmosphere by the anthropogenic burning of fossil fuels. Ocean currents redistribute heat at local and global scales. However, these currents are changing, and their impact on future climate change is not fully understood.

Many societies depend on the ocean directly or indirectly for their livelihood. The ocean provides a significant portion of the world’s protein supply and supports industries such as shipping, tourism and renewable energy.

Cultural, spiritual and recreational values are strongly connected with the ocean. Coastal communities around the world have rich traditions and cultural identities that are tied to the ocean, whether through art, traditions or heritage. Recreational use of the ocean supports mental well-being and contributes to local economies.

2. Changes since the second *World Ocean Assessment*

The third *World Ocean Assessment* builds on previous reports and updates the second *World Ocean Assessment*, which was published in 2021 and covered the period from 2010 to 2018. Each chapter, except for the newly introduced chapters, contains specific information on the progress and changes observed primarily between 2018 and 2023. Most chapters describe all relevant information in relation to various ocean regions. The *World Ocean Assessment* now includes information on sustainability pathways and cross-cutting themes regarding gender; Indigenous, traditional owner and local community knowledge;[1] and governance.

3. Stressors on the global ocean: drivers and pressures

Drivers of ocean change

- Ocean ecosystems and the services they provide continue to be reshaped by multiple interacting drivers, including climate change, economic shifts, technological advances, governance dynamics and demographic trends.
- Understanding these drivers and their cumulative impacts is essential for designing adaptive, forward-looking policies that can safeguard biodiversity, sustain livelihoods and support a resilient blue economy.

The ocean is subject to both natural (e.g. tectonic, solar) and anthropogenic (e.g. greenhouse gas emissions, population growth) drivers, which lead to a variety of stressors and pressures (e.g. atmospheric CO_2 levels, habitat destruction and plastic pollution). Progress is being made to manage these drivers and mitigate pressures; however, many of them continue to negatively affect the ocean, especially its biodiversity, globally (see part 2 below). Although ocean hazards of natural origin are included in subsection 5B, chapter 4, of the *Assessment*, the present overall summary includes them under the subtitle "Ocean pressures" because they are natural processes that can cause significant perturbations in ecosystems and socioecological systems, and because some are mediated by climate change.

Drivers of change to the ocean (sect. 4, chap. 1)

Drivers are widely recognized (e.g. by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) or regional seas conventions) as natural or anthropogenic factors that influence ecosystem structure, function or change.

The following human drivers have the greatest influence on the marine environment:

(a) Human population growth and demographic changes. The global human population increased from 7.7 billion in 2017 to 8.2 billion in late 2024. Currently, approximately 37% of the global population lives within 100 km of the coast, and 11% lives on land that is less than 10 m above sea level. Population pressure heightens demand for food, space and resources, which affects the world ocean, including through habitat degradation;

(b) Economic activity. Global economic growth, measured as a rise in gross domestic product per capita, increased from 2.9% in 2019 to an estimated 3.3% from 2022 to 2024. Global energy consumption has accelerated from an increase of 1.5% per year around 2019 to 2.2% in 2023. Increased urbanization and industrialization have intensified the demand for energy and other resources, putting pressure on the oceans through extraction, production, consumption and waste generation;

(c) Technological advances. Although advances in marine technology offer opportunities, they may also have negative impacts on the world's oceans;

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[1] The nomenclature "Indigenous, traditional owner and local community knowledge" was approved at the eighteenth meeting of the Ad Hoc Working Group of the Whole on 27 March 2023, under the annotated outline of the third *World Ocean Assessment*.

(d) Changing governance structures and social, economic and geopolitical instability. Governance is improving rapidly due to greater global collaboration, but it is also facing major global challenges. To address these challenges, governance policies, politics, administration, and legislation need to be vertically and horizontally integrated globally and across sectors;

(e) Climate change, biodiversity loss and pollution.

The climate change suite of ocean pressures (e.g. warming, sea level rise, acidification, marine heat waves, storm surges and tropical storms) exhibits significant geographical variability. However, these pressures have a particular effect on the coastal domain globally, where they are coupled with other anthropogenic stressors, such as pollution and coastal urbanization. The suite of climate change ocean pressures is increasingly disrupting ecosystem dynamics and contributing to biodiversity loss. These pressures negatively affect the ocean economy, coastal activities and human well-being, health and livelihoods. Due to geographical variability and the various spatial and temporal scales at which these pressures occur, responses and strategies at all levels, from global to local, must be implemented to effectively mitigate their impacts.

Ocean pressures (sect. 4, chap. 6)

The ocean is subject to many anthropogenic pressures. As human activity is concentrated along coasts, coastal habitats suffer the greatest impact from these stressors, coupled with the effects of climate change. The combination of pressures generates cumulative effects that degrade ocean health and marine biodiversity and pose risks to human well-being.

Land-based and marine pollution sources continue to affect the ocean (see sect. 4, chap. 6). Many types of legacy contaminants (such as metals, persistent organic pollutants (POPs) and radioisotopes) and emerging contaminants (such as plastics, pharmaceutical and personal care products (PPCPs) and per- and polyfluoroalkyl substances (PFASs)) have been introduced into the ocean. There is some evidence for a decline in emissions and in precipitation of legacy contaminants such as mercury and some organic compounds in selected areas. However, POPs continue to affect many areas. Levels of pharmaceutical compounds (including antibiotics) continue to increase, particularly in coastal areas. Toxicity studies show significant adverse behavioural effects of PPCPs on marine organisms. Therefore, management action is needed to decrease the presence and potential impacts of pollution in the ocean.

The leakage of plastic waste into the ocean continues to rise globally, especially due to mismanaged waste; microplastic abrasion and loss; littering; and marine activities. There is limited understanding of nanoplastics. Microplastics affect all marine ecosystems, and there is evidence of their impact on over 4,000 species. A reduction in the production of plastics, the development of material science innovations and an increase in recycling and alternatives to single-use plastic are needed.

Global demand for nuclear electricity generation is projected to increase in the next decades as a response to the need to reduce reliance on electricity from fossil fuels. Consequently, this may lead to an increase of radioactive discharges into the ocean.

Non-indigenous species

Non-indigenous species (NIS) continue to spread through various vectors, such as maritime transport. This has significant negative impacts on native species and habitats, with further consequences for economic, social, cultural and human health. Climate change exacerbates the spread and impact of NIS by facilitating their settlement and growth in novel locations due to changes in local environmental conditions.

Erosion and sedimentation

Since the mid-2010s, an increase in the availability of satellite data has enabled the detection of changing coastal erosion and sedimentation patterns and trends. Coastal erosion has significantly intensified in the Arctic, for instance, due to permafrost thawing and increased wave action, which are attributed to sea ice loss and longer ice-free seasons. Consequently, large quantities of nutrients have been released into the Arctic Ocean, which has implications for carbon sequestration and marine ecosystems.

Marine infrastructure

The development of marine infrastructure, particularly in areas beyond traditional coastal zones, has intensified and is exerting significant new pressures and impacts on ocean ecosystems. This development has resulted in the loss or disruption of natural habitats, affecting biodiversity. Wind farms continue to expand farther offshore, putting additional human pressure on understudied marine environments. The rate of construction of oil and gas infrastructure is also increasing, particularly in deeper waters. The installation of seafloor infrastructure, such as pipelines and cables, has a significant impact on continental slopes and submarine canyons. However, there is a growing focus on the development of proactive infrastructure strategies to facilitate adaptation to hazards, including nature-based solutions, buffer zones, physical barriers and systems for early warning and evacuation.

Cumulative effects

Since the publication of the second *World Ocean Assessment*, there has been continued recognition and research on cumulative effects and the need for coordinated management of the oceans. However, global platforms and knowledge bases for mapping human pressures and understanding their cumulative effects are lacking. The assessment of cumulative effects is crucial to preventing ecosystem deterioration.

Ocean hazards of natural origin (subsect. 5B, chap. 4)

Geophysical and geological ocean hazards of natural origin, such as earthquakes, tsunamis and volcanic eruptions, cause deaths and economic losses. Although tectonic subsidence operates on long timescales, it interacts with ocean hazards of natural origin such as flooding, storm surges and sea level rise. These hazards are increasing or are projected to increase due to climate change. Climate change is causing coastal erosion on all continents. By 2050, one third of the low-elevation coastal zone is projected to experience a shoreline retreat of more than 100 m.

Ocean weather and hydrological and climate hazards include tropical storms, meteotsunamis, waves, sea level rise, coastal flooding, marine heat waves, glacial melting, heavy rainfall and river flooding, droughts, saltwater intrusion, acidification and deoxygenation. While these ocean hazards of natural origin are projected to increase or intensify with climate change, they operate over extremely variable time scales. Ocean hazards of natural origin lead to the loss of lives and land; damage to infrastructure and property; disruption of tourism, food systems and livelihoods; coastal flooding and erosion; loss of habitats and biodiversity; loss of cultural and natural heritage; navigational and shipping challenges; and water quality issues, including saline intrusion.

4. Socioecological systems (sect. 5)

One Health (subsect. 5B)

One Health, defined by the One Health High-Level Expert Panel[2] as an integrated, unified approach that is aimed at sustainably balancing and optimizing the health of people, animals and ecosystems, is a useful framework for identifying the linkages and interdependencies in socioecological systems that go beyond the human economic activities. The concept is based on several fundamental principles, including equity, inclusivity, equal access, parity, socioecological equilibrium, stewardship and transdisciplinarity. The World Health Organization (WHO) recognizes its particular relevance to food and water safety, nutrition, the control of zoonoses, the management of pollution and the combating of antimicrobial resistance.

Subsection 5B, entitled "One Health", of the third *World Ocean* Assessment contains a consideration of issues with strong social dimensions – such as human health, well-being, equity, gender and Indigenous, traditional owner and local community knowledge – in tandem with issues that have significant social impacts, such as the role of ecosystems in the carbon cycle, ocean hazards and the effects of the coronavirus disease (COVID-19) pandemic.

The role of marine ecosystems on the carbon cycle (subsect. 5B, chap. 1)

Blue carbon

- Mangroves, seagrasses and saltmarshes – collectively, the first ecosystems to be considered coastal blue carbon ecosystems – hold higher carbon densities than terrestrial forests and host high biodiversity and associated services.
- Although their blue carbon value may be a significant financial resource according to the Paris Agreement under the United Nations Framework Convention on Climate Change, the understanding of their value is currently hampered by insufficient technical capacities for carbon accounting and financial mechanisms.
- Even with full restoration, coastal blue carbon ecosystems would only contribute 2% to the global climate mitigation targets.

The ocean contributes to approximately half of the Earth's annual primary production and supports 80% of global animal biomass. Marine ecosystems play a crucial role in driving the carbon cycle, which is linked to the health and well-being of billions of people due to its impact on climate change regulation and mitigation and their other related ecosystem services, such as food provision.

The biological pump (see subsect. 5B, chap. 1, figure I) is the process by which plankton and nekton drive carbon from the surface of the ocean to the deep sea where it is remineralized by organisms. When carbon reaches depths below 500 to 1,000 m, it becomes sequestered for hundreds to thousands of years. Although only about 2% of carbon fixed at the ocean surface reaches the deep sea, the large spatial extent of the open ocean ensures that it will continue to play a significant role in modulating climate change over decadal to centennial timescales.

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[2] One Health High-Level Expert Panel, "One Health: A new definition for a sustainable and healthy future" *PLOS Pathogens*, vol. 18, No. 6 (23 June 2022).

However, the biological pump consists of a complex array of processes, such as sinking material versus migrating organisms, carbon dynamics within sediments and carbon export from shelf areas towards the open ocean. There is a great deal of uncertainty regarding the relative contribution of those processes and how they differ across geographical areas. Reducing these uncertainties is critical to understanding the role of the ocean as one of the major contributors to carbon sequestration.

Blue carbon ecosystems

The term "blue carbon" was first used for three vegetated coastal ecosystems – saltmarshes, seagrass meadows and mangroves – which capture and store more carbon per unit area than terrestrial forests. The term has been broadened beyond these original coastal blue carbon ecosystems to include other habitats.

Unvegetated seafloor sediments on the continental shelf make up around 9% of the total marine area but store the largest amount of carbon in shelf systems. Over 80% of organic carbon is buried in these subtidal sediments.

The protection and restoration of coastal blue carbon ecosystems are recognized as nature-based solutions and an ecosystem-based approach to mitigating marine climate change. They may contribute to the achievement of nationally determined contributions under the Paris Agreement. Several countries have initiated strategies to enhance the carbon sink capacity of coastal ecosystems through targeted conservation, restoration and management. Recent estimates indicate that, with full restoration, coastal blue carbon ecosystems could contribute about 2% to the global potential for climate change mitigation.

In temperate regions, the small geographic size of these ecosystems makes it unlikely that they will play a significant role in achieving mitigation targets. However, for small island nations, which have a larger geographical extent of blue coastal habitats, the contribution may be significantly higher. Access to international financing and capacity-building, including scientific cooperation, training and the transfer of marine technology, are critical for the assessment and management of blue carbon so as to ensure that efficient methodologies are applied. These actions are already included in various nationally determined contributions and are necessary to achieve global targets.

Macroalgae have recently been suggested as a coastal blue carbon ecosystem. While most algal production is remineralized annually, a fraction is potentially exported to the open ocean or buried in sediments.

While it may seem counterintuitive, calcification by marine organisms, such as corals and bivalves, gives rise to a net emission of CO_2, and, in addition, many calcifiers produce CO_2 through respiration. Recently, coralline algal beds found in sediments have been proposed as blue carbon habitats because the carbon captured and stored through photosynthesis may exceed the CO_2 released by calcification.

Ocean and human health (subsect. 5B, chap. 2) and human well-being (subsect. 5B, chap. 3)

Human well-being and health

- Oceans contribute to human well-being by providing a wide range of non-market benefits, including mental and physical health gains, cultural identity, spiritual fulfilment, recreation and community cohesion. However, these contributions are under increasing pressure from climate change, pollution, habitat loss and unsustainable exploitation, reducing the ocean's capacity to sustain people and nature.

- Human well-being and health both benefit from policies that connect conservation with equitable access, incorporate both market and non-market values, enable community-led stewardship and provide sustainable pathways for balancing human needs with ecosystem health.

The health of the ocean and that of human populations are deeply interconnected. There are many ways in which the ocean has a positive impact on human health. For example, there are benefits related to ocean sporting activities, the consumption of seafood and the development of marine-derived pharmaceutical compounds. Well-being is also associated with the therapeutic and restorative qualities of marine environments, reinforcing the significance of accessible blue spaces for mental and physical health.

Ocean ecosystems contribute greatly to human well-being in ways that extend beyond health. These contributions include economic value and non-market benefits such as spiritual, cultural and recreational services.

The non-market valuation of marine ecosystems, despite its challenges, is crucial for understanding and quantifying the non-monetary value of the ocean, which can enable policy decisions that support both human well-being and environmental health.

Ocean ecosystems play an irreplaceable role in supporting cultural practices, traditional knowledge, intergenerational heritage and social cohesion. This is particularly critical in the case of Indigenous Peoples. Communities interact with and depend on ocean resources, often employing innovative strategies to balance conservation with socioeconomic needs.

The health and well-being benefits derived from ocean ecosystems are at risk due to escalating environmental challenges such as climate change, pollution and resource depletion. Human health is increasingly challenged by harmful algal blooms, pathogenic bacteria and viruses, antimicrobial resistance and toxic chemicals. In addition, environmental radiation can further threaten marine ecosystems. Contaminated seafood poses serious food safety risks and may cause endocrine disruption, neurotoxicity, renal dysfunction, osteoporosis and various cancers.

The integration of cultural, economic and ecological perspectives into ocean management policy ensures that the ocean continues to support human health benefits and well-being, cultural and natural heritage and sustainable development for future generations.

Pandemics, including coronavirus disease (COVID-19) impacts (subsect. 5B, chap. 7)

The COVID-19 pandemic resulted in a mixture of some short-term environmental benefits due to reduced human activity, alongside severe negative consequences for ocean-dependent communities and economies and a rise in pollution levels. The COVID-19 pandemic had severe impacts on the health and safety of seafood workers and coastal communities. High infection risks, declining demand for seafood and a decrease in global tourism disrupted business activities related to fisheries, port operations and supply chains. Many fishing- and tourism-dependent industries and communities faced significant financial losses, leading to increased unemployment and financial insecurity.

The COVID-19 pandemic reduced ocean use, which reduced noise and improved reproduction for some species (e.g. whales). However, the pandemic also negatively affected marine ecosystems. Increased plastic waste, particularly from discarded face masks, threatened marine species. The pandemic also resulted in an increase in the use of specific medications and treatments, resulting in a higher concentration of pharmaceutical residues in marine environments.

Disruptions in scientific research and fisheries monitoring fuelled illegal fishing in certain regions. Due to the pandemic, many new policies were created to address health and safety issues (e.g. workplace safety) in ocean-related employment. Many direct and indirect effects of the COVID-19 pandemic remain unknown, underscoring the need for further research to prepare for future global health crises.

Trends in the physical and chemical state of the ocean (sect. 4, chap. 3)

Physical and chemical changes

- The alteration of the physical and chemical conditions of the ocean due to climate change is accelerating.
- Approximately 16% of the total increase in ocean heat content since 1955 has occurred since 2018. The greatest relative warming has been observed in the Atlantic Ocean and the southern parts of the Indian and Pacific Oceans.
- The sea level continues to rise at increasing rates, from less than 2.0 mm per year prior to 2015 to 4.3 mm per year in 2023. Tropical seas are rising more rapidly due to thermal expansion.
- The extent of Arctic sea ice continues to decrease, and the Southern Ocean has recently shown declines in sea ice extent. The Arctic Ocean could become entirely ice-free in September by the middle of the twenty-first century.
- Ocean CO_2 uptake and ocean acidification continue to increase, although these trends exhibit high spatial and interannual variability due to weather and climate conditions.
- Global ocean deoxygenation persists due to rising water temperature (which reduces oxygen solubility and increases stratification) and intensified microbial activity caused by nutrient run-off from land. Ocean hypoxic zones continue to expand (covering an additional 4.5 million km^2 in the past 50 years).

The ocean continues to capture and store energy and is warming at accelerated rates. Some 16% of the ocean heat content increase from 1955 has occurred since 2018.

Salinity varies greatly across the globe depending on the amount of freshwater input and evaporation; there is no significant global trend in that regard. Since 2018, salinity has decreased in the Pacific, North Atlantic and Southern Oceans but has increased notably in the mid-southern Atlantic and northern Indian Oceans.

The sea level continues to rise at an increasing rate (2.0 mm per year prior to 2015; 4.3 mm per year 2023) due to thermal expansion (especially in tropical regions) and the melting of ice in polar regions. Additional variability is due to storm surges and tectonic and isostatic processes.

The extent of Arctic sea ice continues to decrease, and the Arctic Ocean could become entirely ice-free in September by the middle of the twenty-first century. Currently, the decrease is more apparent in areas influenced by Atlantic and Pacific waters. The decrease of sea ice is resulting in changes to vertical stratification and mixing and further influencing circulation patterns. Southern Ocean sea ice, which had seemed resilient to climate change, has recently shown declines in extent, which is most pronounced in regions south and west of the Antarctic Peninsula, resulting in changes in dense shelf water and associated Antarctic Bottom Water formation.

The weakening of the Atlantic meridional overturning circulation is of particular concern due to its potential impact on the climate of the Northern Hemisphere, especially Europe. None of the recent models implemented by the World Climate Research Programme predict the collapse of the Atlantic meridional overturning circulation during this century, and the confidence level regarding its weakening is medium to low. This contrasts with previous World Climate Research Programme results that had predicted a slowdown of the Atlantic meridional overturning circulation, with some models predicting an abrupt collapse during the twenty-first century. However, other studies have found that the Atlantic meridional overturning circulation is weakening and could reach a tipping point with an abrupt collapse by the middle of the twenty-first century. Atlantic meridional overturning circulation remains a research priority.

Between 1986 and 2022, ocean pH declined by approximately 0.06 to 0.10 units, with significant decreases observed at depths down to 2,000 m. Ocean CO_2 uptake is responsible for the decrease in pH and is highly variable spatially and temporally, but has tripled in the past 60 years (1960–2019), reaching 2.7 ± 0.3 petagrams of carbon per year as of 2019. This value is expected to increase by 0.4 ± 0.1 petagrams of carbon per decade. However, this increase will be attenuated as the rise in temperature reduces CO_2 absorption. Total alkalinity, which is a measure of the capacity of the ocean to buffer acidity, has increased in subtropical regions but varies greatly across the globe.

Global ocean deoxygenation persists due to the combination of increased nutrient pollution, rising water temperatures and intensified microbial activity. Higher water temperatures decrease oxygen solubility and increase ocean stratification. This restricts the vertical exchange of gases, heat, salt and nutrients between surface, intermediate and deep waters, thereby slowing deep ocean ventilation. Ocean hypoxic zones continue to expand (covering an additional 4.5 million km^2 in the past 50 years), and the ocean continues to lose approximately one gigaton of oxygen per year.

Historical nitrogen data reveal differing trends across regions, most likely due to interactions between climate change and other anthropogenic sources and pressures. Recent phosphorous trends deviate from historical baselines, and climate change is expected to increase silica availability in the short term and decrease it in the long term (i.e. in around 150 years), but no global trends have been observed yet. These results demonstrate the need for updated monitoring and for an understanding of these complexities so that future biogeochemical cycles can be accurately predicted.

Biodiversity and habitats

- Anthropogenic, climate and other pressures are causing increasing adverse effects among all the marine taxonomic groups and habitats, from microbes to marine mammals and from the abyssal plains to the coastline.

- Climate change continues to produce impacts across the oceans, especially in high latitudes, where temperature increase and sea ice retreat are causing poleward distribution shifts across all taxa and affecting the dynamics of habitats such as high-latitude ice and fjords.
- Climate-change-related extreme events (e.g. cyclones, marine heat waves or storm surges) occur across all latitudes, and are affecting many habitats, such as coral reefs which are declining rapidly.
- Coastal habitats are, in general, heavily affected by the accumulated impacts of climate change, contamination (including plastics), coastal development, invasive species and nutrient upload.
- Land-use changes and dam construction have drastically changed sediment fluxes, leading to coastal retreat in deltas and estuaries.
- Mangroves, seagrasses and salt marshes are declining worldwide due to pressures such as coastal or aquaculture development, contamination, eutrophication, storm surges, cyclones and invasive species.
- The deepest parts of the ocean (e.g. trenches and abyssal areas) are difficult to access, are poorly understood, lack detailed mapping and is increasingly under pressure as a potential site of resource (e.g. mineral) extraction.
- A diverse array of marine protected areas (MPAs) are being developed and approved as part of marine spatial planning across the globe. International stakeholders are working to establish the first “blue corridors”, or large-scale MPAs, to protect and ensure the long-term health of biodiversity.

Marine biodiversity (sect. 4, chap. 4)

Marine biodiversity encompasses the variety of life forms within ocean ecosystems, and ranges from microbes to large marine mammals. Biodiversity is critical to biological productivity, carbon cycling and climate regulation.

All marine life interacts in complex ways, providing resilience and stability to ecosystems. Since the second *World Ocean Assessment*, marine biodiversity has undergone significant changes, influenced by increasing pressures that are contributing to the worsening global biodiversity crisis. These changes have affected the resources and services provided by marine ecosystems to society worldwide.

Plankton (see sect. 4, subchap. 4A) is the foundation of the pelagic food web and of shelf and deep-sea benthic habitats. It plays a fundamental role in biogeochemical cycles and supports higher trophic levels, including those sustaining fisheries.

The most dramatic changes since the publication of the second *World Ocean Assessment* have been observed in the Arctic Ocean. The increase in phytoplankton biomass is associated with a warming climate and decreasing sea ice coverage, and changes are occurring with respect to the abundance, composition, phenology and distribution of phytoplankton. Globally, phytoplankton blooms are unpredictable and can disrupt carbon cycling and the accessibility of food for higher trophic levels. Zooplankton populations, especially krill, have demonstrated regional declines. The impacts of climate change on plankton in many regions remain unclear, largely due to the limited availability of long-term observational time series.

Cephalopods demonstrate resilience in the face of climate change due to their short life cycles and high reproductive rates, with some populations thriving as a result of increasing temperatures. Nevertheless, distribution patterns have changed, and certain exploited species consistently face pressures from fisheries.

Marine benthic invertebrates (see sect. 4, subchap. 4E), particularly corals, are experiencing increased stress due to the increase in widespread bleaching events caused by elevated sea temperatures. Despite the positive effects observed from conservation efforts and MPAs since the publication of the second *World Ocean Assessment*, there is still a lack of knowledge about deep-sea species, and they remain vulnerable to destructive activities such as trawling.

Fish populations (see sect. 4, subchap. 4D) consistently face challenges due to overfishing and habitat degradation, despite improved fisheries management and reductions in by-catch. While many species of reef fish continue to decline in numbers, some, such as tuna, show signs of recovery because of improved fisheries management measures.

Marine mammals (see sect. 4, subchap. 4E) face persistent risks, including entanglement in fishing gear, collisions with vessels and ingestion of plastic pollution. While some species (e.g. Mediterranean seals and dolphins) have shown slight recovery, others, such as the North Atlantic right whale, remain critically endangered. Moreover, increased underwater noise pollution (e.g. from armed conflict, shipping or offshore infrastructure) is disrupting marine mammal migration and communication.

Marine reptiles (see sect. 4, subchap. 4F), particularly sea turtles, struggle as a result of habitat loss, plastic pollution and climate change. While conservation efforts have led to improved nesting success, general trends are alarming, especially as increasing sand temperatures mean that hatchling sex ratios are skewed towards females.

Climate change similarly affects seabirds (see sect. 4, subchap. 4G), as changes in prey availability influence their reproductive success. Plastic ingestion and by-catch-related mortality has increased, although some bird species have experienced reduced mortality due to modified fishing techniques.

Marine plants (see sect. 4, subchap. 4H), including seagrass and mangrove ecosystems, are essential for coastal protection and serve as key habitat that support marine biodiversity. Pollution and coastal development continue to affect them and reduce their coverage area. Following the publication of the second *World Ocean Assessment*, their climate-mitigating properties have become better known, spurring the development of restoration projects. Macroalgae (see sect. 4, chap. 4I), such as kelp forests, have diminished due to rising water temperatures and changing herbivore populations. While some regions have shown resilience due to conservation efforts, invasive macroalgae increasingly threaten native biodiversity.

Overall, the key findings of the third *World Ocean Assessment* underscore that persistent challenges, including climate change, habitat loss, pollution (particularly from plastics) and overexploitation, confront marine biodiversity. Conservation efforts, strengthened regulations and global cooperation are crucial for mitigating these impacts and preserving the resilience of marine ecosystems.

Habitats (sect. 4, chap. 5)

Marine habitats encompass diverse ecosystems, ranging from shallow coastal zones to deep-sea environments. These habitats are vital for maintaining biodiversity, providing ecosystem services and supporting human livelihoods. However, they are increasingly affected by pollution, habitat loss, climate change and human activities. Sea-level rise, ocean acidification, increased extreme climatic events and habitat fragmentation have all contributed to changes in a variety of marine habitats since the publication of the second *World Ocean Assessment*. At the same time, conservation efforts have grown, with a focus on nature-based solutions, ecosystem restoration and sustainable management techniques.

The intertidal zone (see sect. 4, subchap. 5A) continues to experience significant transformations and habitat loss caused by sea level rise and coastal squeeze. Eutrophication and pollution, including from microplastic accumulation, affect species and ecosystem services. Attempts to use intertidal ecosystems to mitigate climate change have increased. Conservation strategies increasingly use green-grey infrastructure, ecosystem co-design and nature-based solutions.

Biogenic reefs and sandy, muddy, and rocky shores (see sect. 4 subchap. 5B) face intense pressures that threaten biodiversity and disrupt ecosystem functions. Coastal squeeze and human infrastructure already affect 33% of global beaches, with up to 26% at risk of severe sand loss by the century's end. Emergent threats such as plastic pollution (see sect. 4, chap. 6) and artificial light at night further strain these environments, requiring target research and mitigation strategies. Safeguarding coastal habitats requires robust governance that integrates diverse knowledge systems (e.g. Indigenous, traditional owner and local community knowledge) and encourages participatory decision-making. Greater research is needed in tropical and subtropical regions, where data gaps persist, while addressing disparities in coastal management between high- and middle-income countries.

New understanding of atolls (see sect. 4, subchap. 5C), including through the antecedent karst theory and hydrogeology, are challenging previous models of atoll formation. Carbonate sand production and storm-driven sediment transport may help to sustain atoll islands in the face of rising sea levels. Atolls face ocean acidification and warming seas, which weaken reefs and increase coral bleaching. While some remote reefs recover within years, densely populated atolls take over a decade to regenerate. This reinforces the importance of integrated conservation approaches.

Coral reefs (see sect. 4, subchap. 5D) around the world are declining rapidly due to various stressors. Increasing disturbances, such as marine heat waves and storms, leave little time for recovery and are pushing reefs towards collapse. Since 2018, multiple global bleaching events have caused widespread coral mortality. Projections suggest that 90% of reefs could disappear if warming exceeds 1.5°C above pre-industrial levels. Even historically resilient areas, such as the South Atlantic, are experiencing severe losses. Rising hypoxia and ocean acidification add further stress. The Caribbean has lost 80% of its coral cover since the 1970s.

Although cold-water corals and sponges (CWCS) (see sect. 4, subchap. 5E) face increasing threats, new discoveries, such as the extensive reefs on the Blake Plateau, highlight their role in carbon sequestration and ecosystem dynamics. Ocean acidification continues to weaken coral structures and further severe declines are predicted under high-emission scenarios. While advances in CWCS ecology improve the understanding of these fragile ecosystems, long-term monitoring and policy integration remain limited. Expanding protection and global research efforts are urgent priorities.

Changes in estuarine and deltaic environments (see sect. 4, subchap. 5F) have significantly altered sediment dynamics, water quality and ecosystem structures. Since the publication of the second *World Ocean Assessment*, drastic changes in land use and the construction of dams have altered sediment fluxes, resulting in accelerated coastal retreat and subsidence in many areas.

Seagrass meadows (see sect. 4, subchap. 5G) are essential for carbon sequestration, habitat biodiversity and coastal protection. They are declining worldwide, with an overall decline of around 29% since the late nineteenth century. Since the publication of the second *World Ocean Assessment*, marine heatwaves, storms and sea level rise have intensified these declines, especially in East and South-East Asia and certain regions of the North Atlantic. A large area (covering between 66,000 and 92,000 km²) of seagrass beds was discovered in The Bahamas. Major gaps remain, including the need for an update of the global seagrass map, inadequate mapping in deep or turbid waters, insufficient comprehension of climate resilience and carbon sequestration rates, and an absence of conservation policies.

Mangroves (see sect. 4, subchap. 5H) offer important ecosystem services such as coastal protection, biodiversity and carbon sequestration, with an estimated economic value of $65 billion annually. Between 2010 and 2020, net annual mangrove loss declined to 102.4 km², primarily due to conservation efforts, compared with the previous decade. However, losses persist due to aquaculture, urbanization and sea level rise. Notable restoration projects include the goal of China to restore 18,800 ha by 2025, the goal of Indonesia to restore 600,000 ha by 2024 and the initiative of the Islamic Republic of Iran to plant 1,000 ha of mangrove forests.

Coastal development, pollution, sea level rise and invasive species are causing salt marshes (see sect. 4, subchap. 5I) to decline globally. Since the publication of the second *World Ocean Assessment*, losses have continued steadily, with some areas experiencing mangrove encroachment driven by climate change. Although oil and chemical pollution have decreased, the accumulation of plastic is now a major concern.

Continental slopes and submarine canyons (see sect. 4, subchap. 5J) are increasingly affected by direct anthropogenic impacts and by climate change. Fishing, waste dumping, litter and plastic pollution, oil and gas exploration and exploitation, the installation of seafloor infrastructure, noise generation and tourism appear to be the human activities that have the most impact. Despite substantial advances in slope and canyon knowledge, conservation and management, many of the gaps identified in the second *World Ocean Assessment* remain. Most continental slope and submarine canyon habitats remain unexplored and long-term data are limited, making it difficult to assess changes over the past 5 to 10 years.

Since the publication of the second *World Ocean Assessment*, significant changes have taken place in high-latitude sea ice (see sect. 4, subchap. 5K). Arctic sea ice continues to decline, and an ice-free Arctic in September is likely within the next few decades. Meanwhile, Antarctic sea ice, which had gradually increased from 1979 to 2015, has rapidly declined since 2016, possibly indicating a regime shift.

Seamounts and pinnacles (see sect. 4, subchap. 5L) are submerged mountains that support distinctive deep-sea biodiversity, including corals, sponges and economically valuable fish species. Deep-sea fisheries are increasingly exploiting these ecosystems, resulting in habitat degradation. Since the publication of the second *World Ocean Assessment*, conservation initiatives have intensified, resulting in enhanced protection of seamounts by means of MPAs and heightened recognition of their ecological significance. However, despite significant improvements, the understanding of ecosystem dynamics in abyssal seamounts, in seamounts found in areas beyond national jurisdictions and in population connectivity between seamounts remains limited.

Abyssal plains (see sect. 4, subchap. 5M), which are extensive deep-sea areas, are the most understudied marine habitats on Earth. These regions host unique species adapted to extreme conditions and contribute to global carbon cycling. An increasing potential threat from deep-sea mining for rare minerals raises concerns about the resulting potential for habitat destruction and biodiversity loss.

The pelagic domain (see sect. 4, subchap. 5N) is the largest habitat on Earth and plays a crucial role in global climate regulation, carbon cycling and biodiversity. Since the publication of the second *World Ocean Assessment*, advancements in observational technologies and environmental DNA techniques have enabled extensive data collection and supported multidisciplinary studies. The latest Earth system models from the Coupled Model Intercomparison Project have projected greater warming, acidification, deoxygenation and nitrate reductions in the ocean, while new ecological studies, such as trophic amplification, show declining biomass in higher trophic levels.

Recent advances in deep-sea research highlight significant progress in hadal trench exploration (see sect. 4, subchap. 5O), facilitated by new technologies, while progress on exploration of ridge systems remains limited. Since the publication of the second *World Ocean Assessment*, significant findings on mid-ocean ridges have highlighted key areas of biodiversity and the impacts of human activities. The Mid-Atlantic Ridge, for example, exhibits high biodiversity that supports a wide variety of demersal fish and benthic invertebrates. The Arctic Mid-Ocean Ridge, however, faces notable impacts from fishing, mineral extraction and bioprospecting.

Hydrothermal vents and cold seeps (see sect. 4, subchap. 5P) host high levels of microbial and animal biomass that is supported by chemosynthesis and contribute to higher productivity, including of fisheries, in the surrounding systems. Technological advances have enabled the discovery of thousands of these sites in the past, as well as the development of deep oil, gas and gas hydrate activities (seeps) and new mining exploration contracts (vents) issued in the Atlantic and Indian Oceans. Additional pressures on these ecosystems include global warming, deoxygenation, ocean acidification and altered circulation, deep-sea fishing, waste dumping and plastic debris. Conservation actions taken to date include the development of scientific and industry codes of conduct and spatial protection as vulnerable marine ecosystems, MPAs, ecologically or biologically significant areas and the designations on the Red List of Threatened Species of the International Union for the Conservation of Nature and Natural Resources (IUCN).

The Sargasso Sea (see sect. 4, subchap. 5Q) is an iconic high-seas ecosystem that is internationally recognized as a crucial part of the global ocean. Since the publication of the second *World Ocean Assessment*, significant environmental changes have been observed in the Sargasso Sea due to climate change, oceanographic shifts and human activities. Ship traffic in the Sargasso Sea has increased over time.

The fjord systems (see sect. 4, subchap. 5R) of the world are characterized by a deep basin that is connected directly or indirectly to the open sea at the mouth. They are specifically identified as carbon cycle hotspots. Fjords play a crucial role in regulating the carbon cycle over time due to their effectiveness in burying organic matter. Climate change is already affecting both northern and southern hemisphere fjords via warming, deoxygenation and acidification. The loss of glacier ice and the changing seasonality of the hydrological cycle is affecting physical and chemical factors and processes in fjord systems.

Marine food systems

- Seafood sourced from wild fisheries and marine aquaculture accounts for around 20% of the animal protein and 6.7% of the total protein consumed by humans worldwide.
- Fair, transparent and sustainable trade frameworks will help to safeguard small-scale producers, ensure traceability and legality and align seafood markets with climate, biodiversity and food security goals.
- Sustainable seafood processing is a critical lever for enhancing food security, economic resilience and social equity in ocean economies. This includes integrating circular economy approaches, such as the use of renewable energy, the utilization of byproducts and the reduction of emissions.
- Although aquaculture is facing many challenges, including social acceptability, pollution and climate change, it continues to adapt and grow and is increasingly important to ocean economies and essential to food and nutrition security.
- Production from marine capture fisheries has remained relatively stable. However, the proportion of global fishery stocks within biologically sustainable levels has continuously declined.
- Progress is being made across regions with respect to fisheries governance structures and management.
- Sustainable pathways for small-scale and subsistence fisheries must address the cumulative effects of multiple drivers (e.g. social, economic, environmental and climate drivers) of vulnerability, build on the knowledge and experience of fishers and address their concerns about equity, human rights and security.
- Approximately 121 million people worldwide participate in marine recreational fishing. This widespread activity has substantial positive and negative economic and ecological impacts, especially on coastal ecosystems.

Food systems must ensure global food security and nutrition for a population that is expected to reach nearly 10 billion by 2050. Despite its large extent, the ocean provides only 4–8% of human food. Food systems are not only highly dependent on the environment; they also exert significant pressure on it. Close to half a billion people are directly employed in fishing processing and related value chain activities. Sustainable wild fish and mariculture production is the foundation for sustainable trade of marine foods. The uneven geographical distribution of marine resources has historically driven trade from local to global scales, but the proportion of marine production that is exported has increased in recent decades.

Climate change is reshaping the global distribution of seafood. While interregional trade remains dominant for many regions, Asia has become an increasingly important destination. Although trade regulations, certifications and traceability tools are emerging to support sustainable trade of marine foods, unknowns remain regarding their impact and effectiveness.

Due to the high perishability of fish and fishery products and their importance for food, nutrition security and global trade, effective processing techniques are essential for extending shelf life, increasing revenues and enhancing nutritional value (see subsect. 5A, subchap. 1E). In 2022, of the 165 million tons of fish destined for human consumption, about 43% was live, fresh or chilled. This was followed by frozen (35%), prepared and preserved (12%) and cured (10%). This represents about 89% for direct human consumption, with the remaining 11% for non-food purposes such as fishmeal for aquaculture and biofuel.

Since the publication of the second *World Ocean Assessment*, significant progress has been made in prioritizing seafood and aquatic food systems within the United Nations Decade of Ocean Science for Sustainable Development and the Sustainable Development Goals of the 2030 Agenda for Sustainable Development. Technological advances in seafood processing have great potential to promote sustainable growth and food security and to contribute to the conservation of marine ecosystems. As global demand for seafood increases, integrated policy frameworks and value chain improvements must be aligned to foster a more inclusive and resilient industry. Advanced processing techniques, particularly in the areas of traceability and rules of origin, will play a key role in ensuring compliance and meeting the diverse needs of stakeholders. By addressing some of the social and economic issues in coastal communities, the seafood processing industry can play a central role in promoting gender inclusion, fair wages and decent working conditions for all.

Due to uncertainties and a lack of global disaggregated data on small-, medium- and large-scale aquaculture, it is difficult to segregate the contributions and impacts of each subsector (see subsect. 5A, subchaps. 1C and 1D). In the second *World Ocean Assessment*, medium- and large-scale aquaculture refers to commercial orientated production for domestic or export markets, conducted by companies ranging from medium-scale enterprises through to large-scale multinational companies. Between 2018 and 2022, marine aquaculture production increased from 55.7 million tons to 60.2 million tons, and the overall value increased from $76 billion to $89.2 billion.

Over the past two decades, aquaculture production has increased at a rapid pace, and the sector has become more integrated into the global food system. There have been many improvements in farming methods in medium and large-scale aquaculture, as well as major developments throughout aquaculture value chains, with aquaculture products now among the most globalized food items. Digitalization and emerging technologies (e.g. blockchain) are playing an increasingly important role in medium and large-scale aquaculture production. Increased attention has also been paid to the farming of low trophic marine species, including large-scale molluscs and algae. However, issues of social acceptability and environmental impact must be addressed if the sector is to increase production significantly.

Over the past decade, significant efforts have been made to reduce dependence on antibiotics in aquaculture, in particular due to the potential for antimicrobial resistance and its impact on human health. With respect to feed aquaculture (e.g. fish and shrimp), concerns remain about the use of fishmeal and fish oil, overexploitation of wild stocks and feed-food competition.

Climate change also poses challenges for medium and large-scale aquaculture production and the supply chain. Climate-related events affecting marine aquaculture include marine heat waves, harmful algal blooms, deoxygenation and storms. There is a need to focus more efforts on adapting aquaculture production to and mitigating climate change.

The assessment of small-scale aquaculture in subsection 5A, subchapter 1D, involves consideration of two distinct practices: (a) nearshore marine aquaculture (NSMA) and (b) coastal marine aquaculture (CMA). The latter is typically practiced in constructed ponds onshore or in intertidal zones. Small-scale aquaculture plays a significant role in global food security, livelihoods, nutrition and health. On a global scale, most of the world's small-scale production of seaweed, sea cucumbers and sea molluscs are from NSMA, while crustacean production primarily takes place in onshore coastal brackish water ponds and tanks. CMA is dominated by brackish water shrimp and a few species of fish, crayfish and crabs. Some species (e.g. seaweeds and molluscs) and well-managed practices in small-scale aquaculture have a low impact on the health of the ocean.

However, given the potential negative impacts of the aggregation of small-scale aquaculture operations, spatial planning and the consideration of carrying capacity limits should be promoted at the national and regional levels. Over the past several decades, NSMA and CMA have experienced major disease outbreaks. Best management practices, including biosecurity measures, should be implemented to protect the activity and make small-cale aquaculture more sustainable with the least negative impact on the health of the ocean. NSMA and CMA cannot be sustainable without addressing the impacts of climate change and of stressors from land-based sources. In addition, the communities involved in NSMA and CMA are relatively poor and have limited resources, which limits their resilience to climate change.

Small-scale fisheries (see subsect. 5A, subchap. 1B) are of high social, economic, cultural and environmental importance and play a critical role in fostering food and nutrition security for millions of people. Small-scale and subsistence fisheries contribute significantly to national and global economies and are of great social and cultural importance. However, small-scale fisheries are under increasing pressure from declining fish stocks and competition from industrial fisheries. The cumulative effects of a wide range of environmental stressors and climate drivers pose significant threats to the viability and resilience of small-scale fisheries and subsistence fisheries in many regions of the world.

Large-scale fisheries and medium-scale fisheries (see subsect. 5A., subchap. 1A) differ in scale and scope of operations, each with its own set of practices, impacts and sustainability measures. While medium-scale fisheries play a vital role in supporting local economies and livelihoods, Large-scale fisheries operations often have broader environmental and economic impacts that demand careful management and regulation. The third *World Ocean Assessment* emphasizes the importance of ecosystem-based management, transparency, traceability and stakeholder collaboration to mitigate the negative impacts of medium-scale and large-scale fisheries.

Overfishing and illegal, unreported and unregulated (IUU) fishing are among the most pressing concerns when it comes to the sustainable use of the ocean resources. The fraction of global fishery stocks within biologically sustainable levels decreased to 62.3% in 2021, down from 64.6% in 2019, while many others are reaching their full exploitation or are in decline. It is estimated that, globally, between 8 million and 14 million metric tons of unreported catch are illicitly traded each year, representing gross revenues of $9 to $17 billion per year. In addition to the damage to fish populations and ecosystems caused by IUU, the estimated annual economic impact loss due to the diversion of fish from the legitimate trade system is estimated to be between $26 billion to $50 billion.

Marine recreational fishing (see subsect. 5A, chap. 2) is defined as fishing of marine animals (mainly fishes) that are not the individual’s primary source for meeting basic nutritional needs and that are not generally sold or otherwise traded on export, domestic or black markets. Marine recreational fishing contributes billions of dollars annually, especially in developed countries, to local communities through job creation and the promotion of marine stewardship. It is estimated that 121 million people worldwide participate in marine recreational fishing. While the total estimated global marine recreational harvest is about 1% of total commercial landings, recreational removals are generally concentrated in a narrow band of coastal areas, and the impacts are most intense at the local level. The lack of formal recognition of the marine recreational fishing sector is a fundamental problem in fisheries management, contributing to overfishing, conflicts with commercial and subsistence fishers and reduced societal benefits from recreational fisheries. Addressing data gaps, stakeholder collaboration, socioeconomic integration and compliance through education and normative approaches are essential for the effective management of marine recreational fishing and obtaining societal benefit from it.

Sustainable resource use, goals and pathways

- Offshore oil and gas production is continually increasing and accounts for nearly one third of global output, with deepwater and ultradeepwater reserves driving recent exploration growth.
- Although oil spill incidents are trending downward, they cause prolonged ecological disruption, with hydrocarbons persisting in food webs and affecting health, reproduction and population dynamics.
- While offshore renewable energy (ORE) contributes to the global energy transition and to decarbonizing the economy, its implementation requires careful consideration of environmental impacts.
- Over 80% of global trade by volume is shipped by sea. Decarbonizing the shipping sector is crucial because greenhouse gas emissions from ships contribute around 3% of global emissions.
- Tourism in coastal and ocean regions contributes over $5.5 trillion annually and supports approximately 174 million jobs, making it the most significant sector of the ocean economy.
- Tourism can negatively affect the marine environment, but there is a growing role for nature-positive, community-based tourism models that are supported by targeted investments in ecosystems, cultural heritage and inclusive governance.
- Socioeconomic inequalities are reported in many coastal regions, where ocean-dependent communities, particularly women and Indigenous Peoples, often face limited access to markets, capital and technology.
- Equity in ocean governance is essential to ensuring that the benefits, responsibilities and opportunities of ocean use are shared fairly among all stakeholders, including women, youth, Indigenous Peoples and marginalized communities.
- Including gender perspectives into ocean governance enhances the resilience and effectiveness of conservation and management initiatives.

Sustainable resource use refers to the management of ocean resources in a manner that satisfies present needs without compromising the ability of future generations to meet their own needs. The sustainable use of natural resources is key to global environmental, economic and social stability. The ocean plays an essential role in this process by regulating the climate, maintaining biodiversity and providing critical resources for humanity, such as food, minerals and energy.

Observed trends in ocean renewable (see subsect. 5A, subchap. 3A) and non-renewable (see subsect. 5A, subchap. 3B) technology developments include offshore wind farms and tidal and wave energy systems. While renewable energy developments are focused on efficiency and cost reduction, efforts to explore non-renewable energy sources continue despite concerns about potential adverse environmental impacts. However, more sustainable approaches are emerging.

Emerging trends, such as increased global interest in ORE and growing awareness of the importance of ocean conservation, present opportunities and challenges. As the world moves towards a more sustainable future, it is essential to balance the benefits of using ocean resources with the necessity of protecting marine ecosystems and securing social equity.

Despite its many positive aspects for humans, the rapid growth of coastal tourism (see subsect. 5A, chap. 4) can also lead to habitat destruction, pollution and the overexploitation of marine resources, such as coral reefs and fish stocks. Unsustainable tourism contributes to marine pollution, including plastic waste, noise and the hazard of oil spills, which harm marine life. Overcrowding at popular destinations can degrade local ecosystems and adversely affect the well-being of coastal communities. Emerging sustainable tourism practices, such as responsible waste management, eco-friendly infrastructure and community-based conservation, are crucial to mitigating these impacts and securing sustainability.

Shipping (see subsect. 5A, chap. 6) accounts for more than 80% of all world trade in goods by volume. It plays a critical role in global commerce by enabling the movement of goods and connecting businesses with customers worldwide. However, the global shipping fleet accounted for approximately 3% of total global greenhouse gas CO_2 emissions in 2023, and estimates show that this figure could increase by 90–130% above 2008 levels by 2050. In times of unprecedented climate and environmental changes, sustainable shipping is of critical importance. Examples of sustainable approaches include the use of cleaner fuels, the use of technologies that reduce carbon emissions and the optimization of shipping routes to minimize environmental impact.

About 90% of commercial vessels use bunker fuel, a highly polluting energy source. This makes it difficult to significantly reduce emissions in the near future, as more than 70% of newly planned ships will continue to use traditional fuels. In addition to greenhouse gas emissions, shipping causes other types of environmental pressure, including chemical, biological and energy pollution. Therefore, environmental regulations, driven by concerns about pollution and climate change, are becoming increasingly rigorous.

Ocean water desalination and salt production (see subsect. 5A, chap. 8) are increasingly reliant on renewable energy, applied to support desalination plants. Technologies based on reverse osmosis and electrodialysis are improving efficiency. Salt production methods worldwide are rapidly evolving towards sustainable practices.

Since the publication of the second *World Ocean Assessment*, the search for and use of marine genetic resources (see subsect. 5A, chap. 5), as well as the development of marine biotechnology, have continued to grow rapidly. Advances in marine genomics have led to many discoveries in the fields of sustainable bioproducts, pharmaceuticals, and biofuels. Although marine genetic resources hold immense potential, they remain largely understudied. Most areas beyond national jurisdiction, including the deep sea, are still unexplored.

Mineral resources

The exploration and exploitation of marine mineral resources in maritime areas under national jurisdiction has been driven by demand. While deep-sea mineral exploration has occurred both within and beyond national jurisdiction, commercial exploitation has not begun. The sustainable exploration and potential exploitation of marine mineral resources depend on scientific and technological innovation, stakeholder participation and reliable information to effectively evaluate environmental, social and economic impacts (see subsect. 5A, chap. 7).

Socioeconomic inequalities are reported in many coastal regions, where ocean-dependent communities, particularly women and Indigenous Peoples, often face limited access to markets capital, and technology (see subsect. 5B, chap. 5). Therefore, policies aimed at creating an inclusive ocean economy should emphasize social equity, access to resources and the participation of persons in marginalized situations in decision-making processes.

While ocean industries such as fishing, tourism and renewable energy contribute significantly to economic growth, they also present challenges in terms of wealth distribution and access to resources. Therefore, the concept of an inclusive economy is crucial for ensuring that ocean resources yield benefits and that such benefits are distributed in a fair manner across society, including persons in marginalized situations.

The Sustainable Development Goals contain a strong focus on the importance of gender equality in all aspects of sustainable development, including the governance of ocean resources. Integrating gender perspectives into ocean policies ensures that the needs, perspectives and rights of women are recognized and also ensures inclusive and effective management of marine resources (see subsect. 5B, chap. 6).

Gender-oriented policies and programmes that provide women with equal access to resources, decision-making power and economic opportunities are crucial for promoting both gender equality and the sustainability of ocean resources.

Ocean governance

- The recent adoption 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 marks a milestone in extending conservation and sustainable use of biodiversity into areas beyond national jurisdiction, reinforcing modern environmental standards and equitable benefit sharing. The Agreement opens up a new pathway for internationally recognized area-based management tools, including MPAs for the high seas.
- However, the challenge continues to be the overcoming of institutional and thematic fragmentation, which would ensure that global, regional and national efforts are aligned under shared principles such as the ecosystem approach, the precautionary approach and the best available science.
- The third *World Ocean Assessment* is the first integrated ocean assessment to include an ocean governance section.

- The fragmentation of ocean governance at the global and regional levels has continued to draw significant attention over the past five years, and various mechanisms have been developed, including cross-sectoral interplay, systemic responses such as judicial proceedings, and other mechanisms that strengthen and foster multilevel cooperation such as in the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction.
- The application of ocean governance concepts across global and regional institutions strengthens legal connectivity, enhancing coherence and synergies in governance.

Ocean governance (see sect. 3) is underpinned by a highly complex and dynamic interplay of States, multilevel intergovernmental institutions and regimes, in which concepts, principles and means of implementation are developed and used.

The United Nations Convention on the Law of the Sea of 1982 sets out the legal framework within which all activities in the ocean and seas must be carried out.[3] Other global treaties have been progressively agreed in the past 70 years, including two agreements, the Agreement on Fisheries Subsidies, which entered into force in 2025, and the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, which entered into force in 2026. These treaties address various aspects of the marine environment, including biodiversity protection, harmful fisheries subsidies, pollution from sectoral activities and other threats to the marine environment.

In addition, many non-binding instruments and associated intergovernmental policy processes are focused on the marine environment. These processes can facilitate cooperation, action and coordination among States (e.g., in the case of United Nations mechanisms such as UN-Oceans) or the development of a common scientific understanding (e.g. through the Intergovernmental Panel on Climate Change (IPCC), IPBES, the World Ocean Assessment and the United Nations Decade of Ocean Science for Sustainable Development).

However, the fragmentation of ocean governance at the global and regional levels has continued to draw significant attention since the publication of the second *World Ocean Assessment*. In recent years, new binding and non-binding instruments have been developed to strengthen the existing governance framework and address gaps in ocean governance, including mechanisms for cross-sectoral interplay (e.g. the Convention on Biological Diversity; the Kunming-Montreal Global Biodiversity Framework of 2025; the Agreement on Fisheries Subsidies of 2025; the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction of 2026; and the International Maritime Organization (IMO) greenhouse gas emissions strategy of 2023).

The application of ocean governance concepts across global and regional institutions strengthens legal connectivity, enhancing coherence and synergies in governance.

Over the past five years, the areas of concern of relevant intergovernmental institutions have expanded beyond traditional marine environmental issues (e.g. pollution and fisheries) to include more recent priorities such as climate change mitigation, plastic pollution, ocean monitoring and observation, food security, maritime security, migration by sea and human rights.

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[3] See the second *World Ocean Assessment*, at www.un.org/regularprocess/woa2, and General Assembly resolution 79/144.

Overarching objectives such as sustainable and inclusive ocean economies, blue health and blue justice are playing a significant role in ocean governance, and the social sciences are becoming increasingly relevant in that regard.

5. Marine observations and ocean knowledge

Marine observations and technological developments advancing scientific understanding of the ocean

Effective ocean management, decision-making and policies must be based on observations, information and scientific knowledge acquired through an extensive and diverse array of methodologies and technologies used by multiple disciplines, including the social sciences. Technologies and methodologies for ocean observation are developing rapidly and, together with advances in modelling, they are greatly increasing the scientific understanding of the ocean and the development of management tools. These advances are partially responsible for the progress made since the publication of the second *World Ocean Assessment*. However, significant gaps remain when it comes to the knowledge of vast areas and important components of the ocean. There are also inequalities in access to data and technologies, as well as in scientific capacity across regions.

The use and development of automated or semi-automated ocean observation platforms, such as Argo floats (which are now being expanded to include deep Argo floats that observe depths below 2,000 m), gliders, submarine cables, unmanned autonomous vehicles, remote observing vehicles and drones, continue to expand. These platforms provide valuable data and information at an increasing range of spatial and temporal scales and resolutions below the ocean’s surface. The observation of the ocean’s surface was revolutionized decades ago by the use of satellites. However, the deeper domains of the ocean remain the subject of a major knowledge gap due to the challenges of observing deep waters, especially those far from the coast. This will be a major challenge during the implementation of the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction. Nevertheless, significant progress has been made in identifying hotspots of biodiversity in deep-sea habitats, such as seamounts, submarine canyons, trenches and hydrothermal vents.

Newer observation platforms are equipped with higher-resolution and more precise sensors, as well as sensors that can measure new variables. Examples include the use of higher-resolution satellite sensors, the incorporation of biogeochemical variables into Argo floats, advances in image acquisition systems and the use of passive and active acoustic sensors in biological studies, including of fisheries. The critical importance of automated data acquisition systems was revealed when non-automated monitoring systems were interrupted during the COVID-19 pandemic.

However, the acquisition of real-time or near-real-time data is skewed towards physical variables rather than biological variables, with biochemical variables falling somewhere in between. This imbalance is due to the complexity of the biological components of marine ecosystems, the diverse nature of their variables (e.g. taxonomic, ecological and physiological), the lower number of sensors developed for biological variables and the energy consumption required for image acquisition systems and active acoustic sensors. Nevertheless, image acquisition systems and advances in acoustic technologies have significantly improved the understanding of biodiversity, species distribution patterns and fisheries management.

Nevertheless, research vessels are still essential platforms for studying the biogeochemical and biological components of the ocean, as well as for managing biological resources, such as fisheries, and for the conservation of biodiversity, habitats and ecosystems. In most cases, samples must still be processed in a laboratory.

The advancement and expansion of biomolecular technologies, such as genetic sequencing, in situ sequencing platforms, synthetic biology, metagenomics and environmental DNA/metabarcoding, have led to significant progress in biodiversity and ecology studies across all taxonomic groups, habitats, fisheries, aquaculture and MPA implementation and management. Nevertheless, the application of these techniques is limited. For example, the study of biodiversity still requires on-the-ground verification by expert taxonomists. Unfortunately, the number of taxonomists is decreasing globally, which has become a serious concern.

Furthermore, long-term monitoring and observation systems are needed to understand long-term ecosystem dynamics, including the effects of climate change, as well as for management and decision-making purposes. International initiatives such as the Argo programme and the Global Ocean Acidification Observing Network, which are coordinated under the Global Ocean Observing System, as well as more recent programmes under the Ocean Decade, continue to reinforce international cooperation and assist with the implementation and standardization of methodologies and ocean indicators. However, long-term monitoring programmes are often hindered by a lack of adequate long-term funding.

Modelling is now widely used across all disciplines to study phenomena such as climate change, ocean circulation, species distribution, erosion and sedimentation, food web dynamics and fisheries and aquaculture. It contributes to progress in scientific understanding and serves as a management tool. The implementation of digital twins of the ocean and the application of artificial intelligence are particularly promising for management decisions. However, both digital twins and artificial intelligence require extensive data sets that adhere to the FAIR (findable, accessible, interoperable and reusable) principles. Although many data remain inaccessible, initiatives such as the European Marine Observation and Data Network, the Bureau of Ocean Energy Management, the Mid-Atlantic Ocean Data Portal and the International Oceanographic Data and Information Exchange are helping to meet the demand for data.

As discussed in section 3 on ocean governance (and further in sect. 4, chap. 1), effective decisions for the sustainable management of the ocean require the incorporation of social sciences. Therefore, ocean observation systems must integrate social variables, and social science must be increasingly incorporated into knowledge systems.

Indigenous, traditional owner and local community knowledge

- Indigenous, traditional owner and local community knowledge is increasingly being acknowledged as a valuable component of knowledge systems and ocean governance models. Effective knowledge systems are challenged by a persistent failure to recognize or engage with diverse world views, including Indigenous ways of knowing. Ocean governance models that incorporate Indigenous, traditional owner and local community knowledge are more likely to achieve comprehensive marine ecosystem and well-being outcomes.

“Indigenous, traditional owner and local community knowledge” collectively refers to knowledge systems developed by Indigenous Peoples, traditional communities and local communities through extended close interaction with their surrounding environment or long-standing continuous culture (see subsect. 5B, chap. 8, for an in-depth description). Indigenous, traditional owner and local community knowledge is increasingly being acknowledged as a source of information complementary to classical scientific information.

There is growing recognition that Indigenous, traditional owner and local community knowledge can provide insights valuable for sustainable resource management and biodiversity conservation. The loss of biodiversity and habitat is not only a significant ecological loss, but also leads to the loss of cultural identity. The cultural assets of most Indigenous, traditional and local communities are linked to the natural environment and significant changes in these environments can undermine the cultural security of these communities. The impacts of change (e.g. climate change) differ across societal and cultural groups and may vary greatly between Indigenous Peoples and non-Indigenous peoples. Certain social classes and groups will be affected differently from others. There has been a recognition of the need to meaningfully weave Indigenous, traditional owner and local community knowledge throughout the third *World Ocean Assessment* in order to capture a more holistic understanding of the state of the marine environment and inform sustainable ocean governance.

The ocean is an essential part of the planet's life support system. Improving its health is crucial to the sustainability of marine ecosystems and the well-being of all life on Earth. Scientific understanding of the ocean must be advanced from an interdisciplinary perspective and across spatial and temporal scales if human activities and climate-related impacts are to be managed effectively.