Future Science Brief

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Deep Sea

Research and Management Needs

European Marine Board
Advancing Seas & Ocean Science

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European Marine Board IVZW

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The European Marine Board (EMB) is an independent and self-sustaining science policy interface organisation that currently represents 38 Member organisations from 19 European countries. It was established in 1995 to facilitate enhanced cooperation between European marine science organisations towards the development of a common vision on the strategic research priorities for marine science in Europe. The EMB promotes and supports knowledge transfer for improved leadership in European marine research. Its membership includes major national marine or oceanographic institutes, research funding agencies and national consortia of universities with a strong marine research focus. Adopting a strategic role, the European Marine Board serves its Member organisations by providing a forum within which marine research policy advice is developed and conveyed to national agencies and to the European Commission, with the objective of promoting the need for, and quality of, European marine research.

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European Marine Board IVZW Future Science Brief N° 12

This Future Science Brief is a result of the work of the European Marine Board Expert Working Group on Deep Sea and Ocean Health. See Annex 1 for the list and affiliations of the Working Group Members.

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Foreword

The deep sea, often referred to as the last great unexplored frontier on Earth, is a critical component of our planet's life support system. Yet, it remains significantly underrepresented in policy considerations, and crucial research needs are frequently side-lined. Many deep-sea species remain undescribed, and many natural functions and services are poorly understood. With increasing human activities in the deep sea, the need for robust, evidence-based decision-making has never been more pressing.

In 2015, EMB published Position Paper N°. 22 “Delving Deeper: Critical challenges for 21st century deep-sea research”, followed by the accompanying Policy Brief N°. 2 “Delving Deeper: How can we achieve sustainable management of our deep sea through integrated research?”. These documents highlighted the critical challenges and knowledge gaps in deep-sea research and management, and underscored the urgency of addressing these gaps, particularly in the face of growing industrial pressures. In the last decade, significant strides have been made in deep-sea research, yielding a substantial body of knowledge about its ecosystems, inhabitants, and the impacts of human activities. However, despite these investments, our understanding remains fragmented, with data often limited to specific regions, parameters, or species. This lack of comprehensive, spatial and temporal knowledge hinders our ability to model and forecast changes in the deep sea, which are essential for informing policy and identifying priority areas for conservation and sustainable use of its resources.

The European Marine Board selected the topic of the deep sea and Ocean health for a new activity in Autumn 2021. The Working Group kicked-off in February 2023 with a meeting at the InnovOcean Campus (Ostend, Belgium) hosted by the EMB Secretariat. I am pleased to present this strategic document that underscores the urgent need to address the continued knowledge gaps on the deep sea to ensure the health and sustainability of our Ocean, both now and for future generations. The document also highlights the legal aspects of managing the deep sea such as the recent BBNJ Agreement, together with other UN instruments. These require evidence-based sustainable use of the deep sea at an international level, while we rely on EU and national laws to manage waters within the Exclusive Economic Zones (EEZs). The document makes a series of recommendations which support the Mission to Restore Our Ocean and Waters by 2030 and the UN Decade of Ocean Science for Sustainable Development. These recommendations provide guidance for policy and management, for research and monitoring of the deep sea as well as for our efforts to build capacity globally.

On behalf of the European Marine Board, I extend my gratitude to the Working Group Members and additional contributors for their collaborative effort in writing this document, bringing together diverse perspectives and approaches. I want to especially mention Sylvia Sander, Christian Tamburini and Sabine Gollner for their leadership in the finalisation of the publication. I would also like to thank the external reviewers and the experts at the EMB Member Organisations for their constructive comments. Finally, I would like to thank the EMB Secretariat, in particular Ángel Muñiz Piniella, for exemplary coordination of the Working Group and for steering the writing, editing and reviewing of this document from inception right through to publication.

Fiona Grant
Chair, European Marine Board
April 2025

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Executive summary

The deep sea, defined here as the Ocean space below 200 m depth, plays a crucial role in the health of the global Ocean and the planet as a whole. The deep sea encompasses 90% of total Ocean volume, hosts diverse ecosystems with potentially millions of (mostly unknown) species, and provides essential ecosystem services and functions. Humanity as a whole benefits from the deep sea. However, many of the benefits derived from the Ocean, and the deep sea in particular, are unknown or not well understood. Yet, essential ecosystem functions and services such as nutrient cycling, carbon sequestration and support for marine biodiversity are under threat. The Ocean absorbs 90% of excess global heat and a quarter of excess carbon dioxide, serving as a buffer against climate change, but by doing this it is also putting deep-sea ecosystems under pressure due to warming, acidification, and deoxygenation. In addition, activities in the deep sea such as oil and gas extraction, fishing, and potential new activities like seabed mining and marine carbon dioxide removal may pose a threat to critical ecosystem functions and services. Despite the importance of this biome, deep-sea research faces significant challenges due to logistical and financial constraints, resulting in notable knowledge gaps. Measuring and understanding baseline conditions in the deep sea, and the impacts of human activities is crucial for informed decision-making and sustainable management of a healthy Ocean and planet. To address these challenges, substantial investments in deep-sea research and management are necessary, and below we highlight important policy, management and research recommendations to ensure a healthy Ocean and deep sea. More detailed information on the targeted funders and outcomes, suggested timelines and assessment criteria are set out in Chapter 6.

Recommendations for policy and management to sustain Ocean health for future generations:

The European Union (EU) and European nations should take an active role in leading international efforts to protect and sustainably manage the deep sea through:

(1) **Effectively governing human activities in the deep sea** within EU jurisdiction and in areas beyond national jurisdiction (ABNJ), in alignment with 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 (BBNJ Agreement) and relevant EU and international laws.

(2) **Establishing an international scientific committee for deep-sea sustainability and protection** to identify key areas to be monitored and protected, with the goal of reaching the Global Biodiversity Framework Target of 30% protection by 2030, and to be able to provide recommendations for funding essential scientific projects.

(3) **Contributing to develop and implement standardised deep-sea Environmental Impact Assessment methodologies** in order to understand and manage human impacts and the associated risks in the deep sea.

Recommendations for funders, research and monitoring, to increase our understanding of Ocean health over time and space:

National and European research funders should support research and monitoring to help close significant knowledge gaps in understanding Ocean processes and connectedness over space and time through:

(4) **Supporting transdisciplinary research programs to better understand the role of the deep sea in Ocean (and human) health.** This includes, but is not limited to, disciplines of natural sciences, social sciences and humanities, law, indigenous knowledge, engineering, and technology. These programs should aim for a holistic understanding of interactions between the deep sea, Ocean and planetary health.

(5) Investing in long-term monitoring of the deep sea. Long-term, regional, and basin-scale multidisciplinary monitoring programs need to be established, and existing ones should remain operational, to describe baselines, capture shifting baselines under climate change and other anthropogenic impacts, and ensure effectiveness of protected areas.

(6) Launching large-scale and long-term multidisciplinary natural sciences projects to increase knowledge of global deep-sea processes.

(7) Supporting research efforts in specific critical research fields, such as, but not limited to, advancing genomic sequencing and taxonomy, and increasing our knowledge on: (i) the metabolic consequences of species adaptation to climate change through experimental studies; (ii) cumulative and synergistic impacts on deep-sea species; (iii) the (mid-water) biological carbon pump, (iv) the rate of change of deep-sea temperatures; (v) the Meridional Overturning Circulation (MOC) and its impact on upwelling and downwelling processes; and (vi) abiotic and biotic subseafloor processes and their connectedness to Ocean processes.

Recommendations for global capacity building to better understand and manage the deep sea:

International cooperation and multilateral action should ensure that all countries have sufficient capacity and appropriate technology to actively engage in scientific research and Ocean management, in order to implement the 2023 BBNJ Agreement effectively. This may be achieved by:

(8) **Enhancing educational, training, and research opportunities for all current and future scientists addressing their unique regional challenges**, particularly those from underrepresented regions, as a way to implement science as a global fundamental human right.

(9) **Fostering the transfer of marine technology and developing training programs**, to increase the number of deep-sea research initiatives by underrepresented nations.

(10) **Continuing to promote the Findability, Accessibility, Interoperability, and Reusability (FAIR) Data principles.**

Contribution to the UN Decade of Ocean Science for Sustainable Development (Ocean Decade) Challenges and Outcomes

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

This Future Science Brief and its recommendations support the UN Decade of Ocean Science for Sustainable Development's (Ocean Decade's) societal outcomes (O1 – O7) and challenges (C1 – C10) in the following ways:

- **"A healthy and resilient Ocean"** (O2) where marine ecosystems are understood, protected, restored and managed, and **"Protect and restore ecosystems and biodiversity"** (C2) by recommending the establishment of a European scientific committee for deep-sea protection, and supporting efforts in specific critical research fields to better understand Ocean health over time and space.
- **"A productive Ocean"** (O3) supporting sustainable food supply and a sustainable Ocean economy, and **"Develop a sustainable and equitable ocean economy"** (C4) by promoting better governance of human activities in the deep sea and recommending the development and implementation of standardised deep-sea environmental impact assessment methodologies in order to understand and manage human impacts and the associated risks in the deep sea.
- **"A predicted Ocean"** (O4) where society understands and can respond to changing Ocean conditions, and **"Unlock ocean-based solutions to climate change"** (C5) by recommending transdisciplinary research programs to better understand the role of the deep sea in Ocean (and human) health, and to improve our knowledge of global deep-sea processes, including their role in regulating the climate.
- **"An accessible Ocean"** (O6) with open and equitable access to data, information and technology, and innovation, **"Expand the Global Ocean Observing System"** (C7), and **"Skills, knowledge and technology for all"** (O9) by promoting the FAIR principles and investing in long-term monitoring of the deep sea; and advocating for the global recognition of science as a fundamental human right on a global scale, the transfer of marine technology to underrepresented nations and the development of training programs to increase the deep-sea research capacity globally.

This publication is endorsed by the United Nations Decade of Ocean Science for Sustainable Development as a Decade Activity. Use of the United Nations Decade of Ocean Science for Sustainable Development logo by a non-UN entity does not imply the endorsement of the United Nations of such entity, its products or services, or of its planned activities. For more information please access: https://forum.oceandecade.org/page/disclaimer

Contribution to the EU Mission: Restore our Ocean and Waters

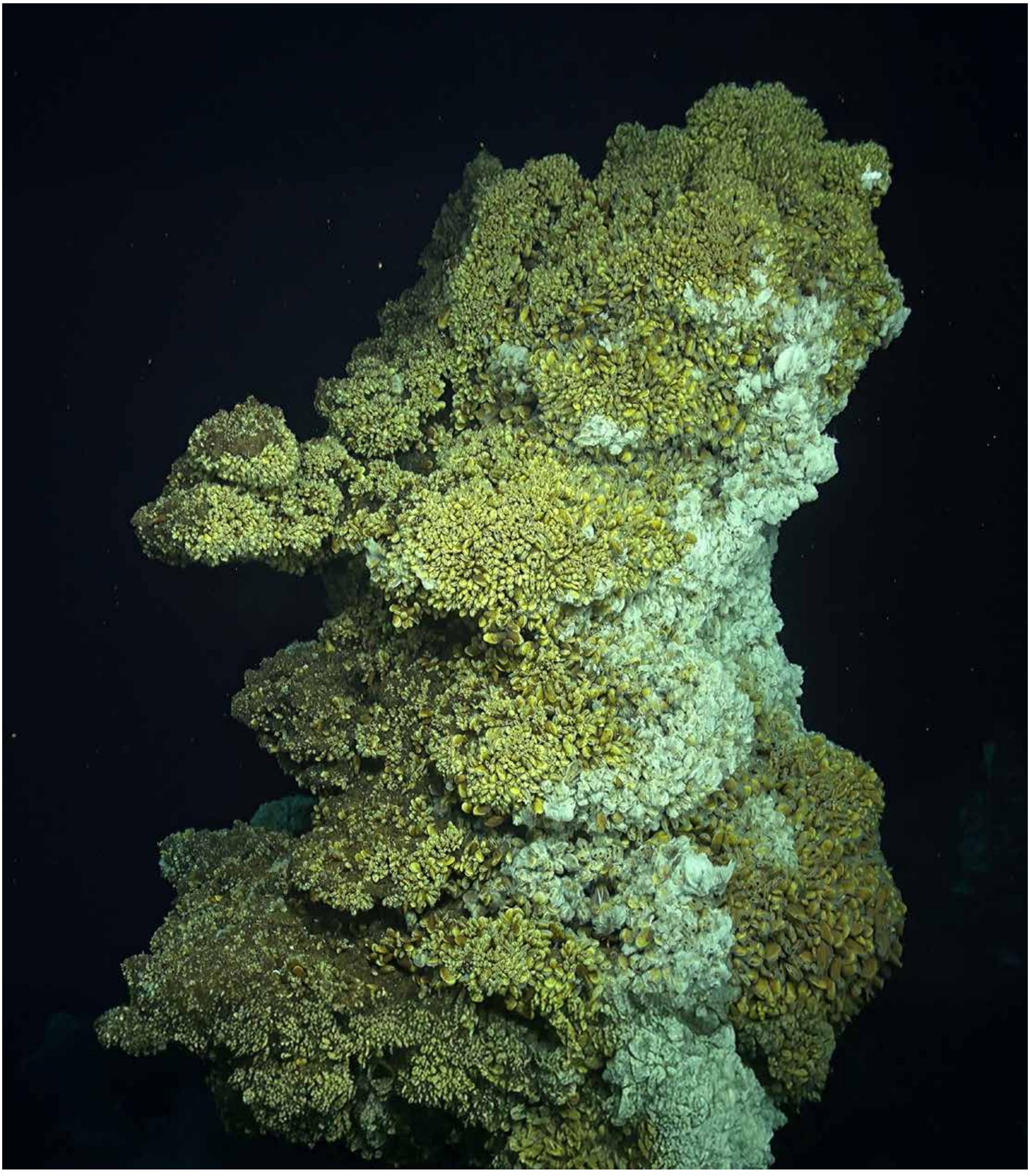
This Future Science Brief and its recommendations support the objectives of the EU Mission: Restore our Ocean and Waters in the following ways:

- **"Protect and restore marine and freshwater ecosystems and biodiversity"** by promoting a better understanding of the role of the deep sea in Ocean (and human) health and by recommending the establishment of a European scientific committee for deep-sea protection.

And the cross-cutting enabling action:

- **"Digital Ocean and water knowledge system"** by promoting the FAIR principles for deep-sea research data to better understand the temporal and spatial patterns and trends in the deep sea.

The European Marine Board acknowledges that while the Working Group members who wrote this document and its recommendations represent diversity in terms of European geographical location (see Annex 1), professional background, gender and career level, their views may not represent ideas from all forms of diversity. This document has a European focus, but its messages and recommendations are relevant to stakeholders globally. The diversity in expertise in the Working Group has been crucial in highlighting different views and perspectives on the deep sea from different communities and to address the complexity of the topic, leading to the common messages in this document.



Credit: Riwan Leroux, Ifremer, cruise Momarsat 2024

Detail of the Bairro Alto edifice at the Lucky Strike hydrothermal vent field (near the Azores) at 1,647 m depth, covered with mussel beds and white filamentous microbial mats.

1 Understanding the complexity of the deep sea and its role in Ocean health today

1.1 Humans and the deep sea: a short history and foresight

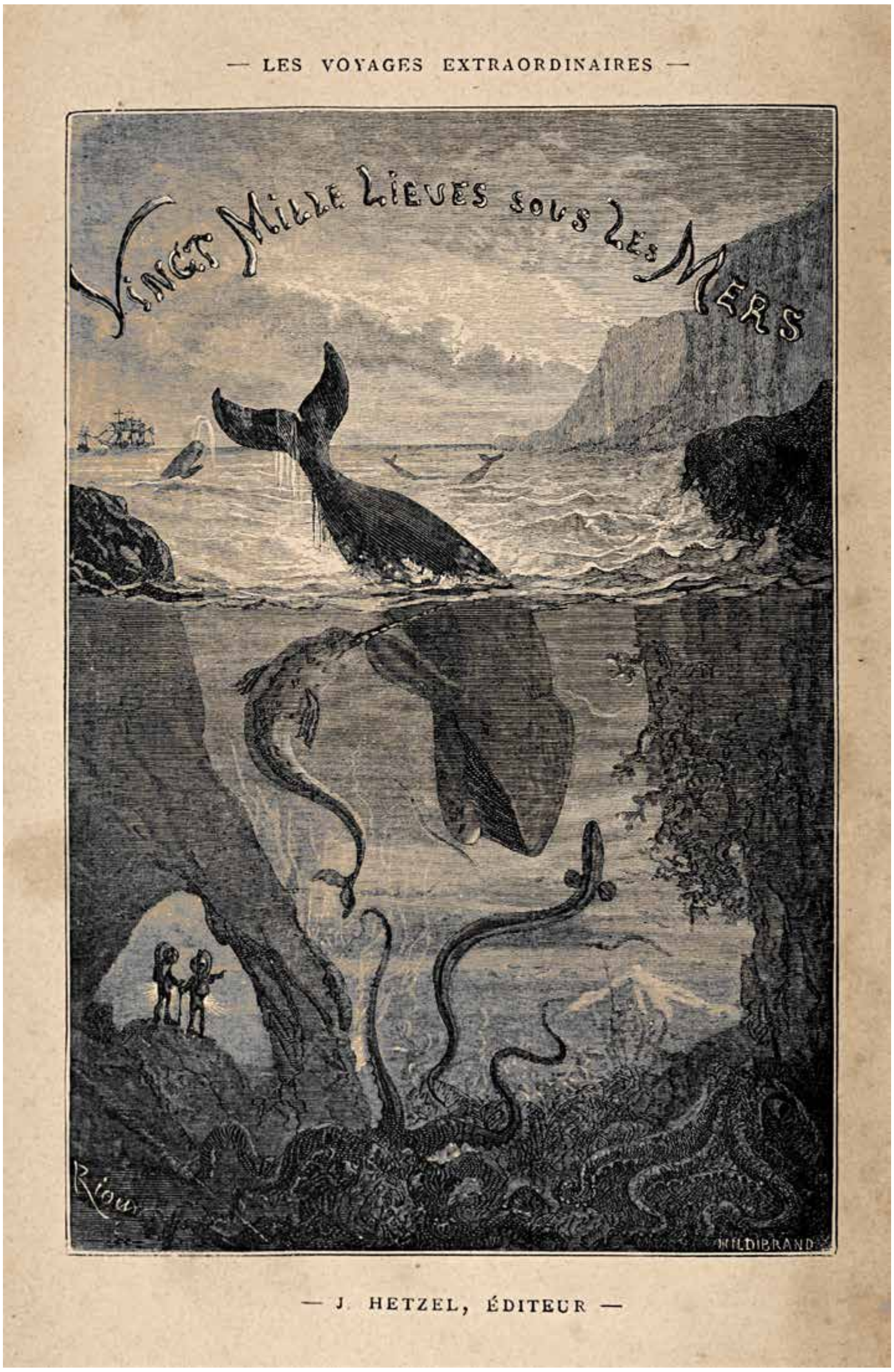


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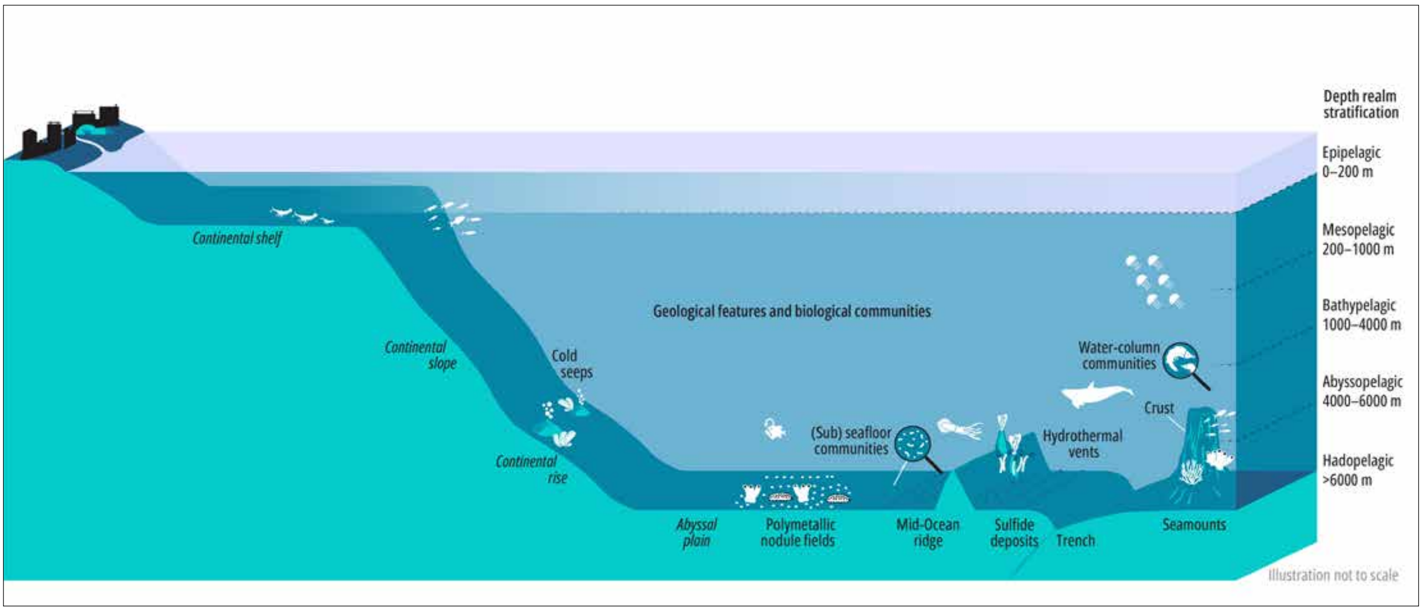
Figure 1.1 Cover of the first edition of the science fiction novel "Twenty Thousand Leagues Under the Sea", by French writer Jules Verne from 1871, demonstrating the adventurous and romantic perception of the deep sea at the time.

The Challenger Expedition (1872-1876) is commonly recognised as the beginning of deep-sea scientific research. The discovery of living organisms at great depths disproved the theory proposed in the 1840s that marine life would be impossible below 550 m depth where there is no light (Anderson & Rice, 2006). Jules Verne's novel "Twenty Thousand Leagues Under the Sea" (1871) (Figure 1.1) already illustrated human fascination with the deep sea. Today, it is well known that the deep sea hosts diverse life forms down to the deepest parts.

The definition and characterisation of the deep sea vary based on context, discipline, or practice. In this Future Science Brief, the term is used to refer to the marine environment exceeding 200 m depth, below the sunlit upper layer (euphotic zone). Geological features (e.g. continental shelves, abyssal plains, seamounts, canyons, mid-Ocean ridges, hadal trenches) and biological communities (e.g. soft-sediment, hard-substrate, cold-water corals, sponge grounds, hydrothermal vents, cold seeps, meso-, bathy-, abysso-, hado-pelagic and benthic) structure the enormous four-dimensional volume (i.e. three-dimensional space evolving over time) of the deep sea (Figure 1.2), that reaches down to 11,000 m depth, with an average depth of ca. 3,700 m. Legally, the deep sea is undefined and falls under a complex and fragmented landscape of overlapping legal frameworks and governance regimes, encompassing areas within and beyond national jurisdiction[1] (Figure 1.3 and see Chapter 2 for more details).



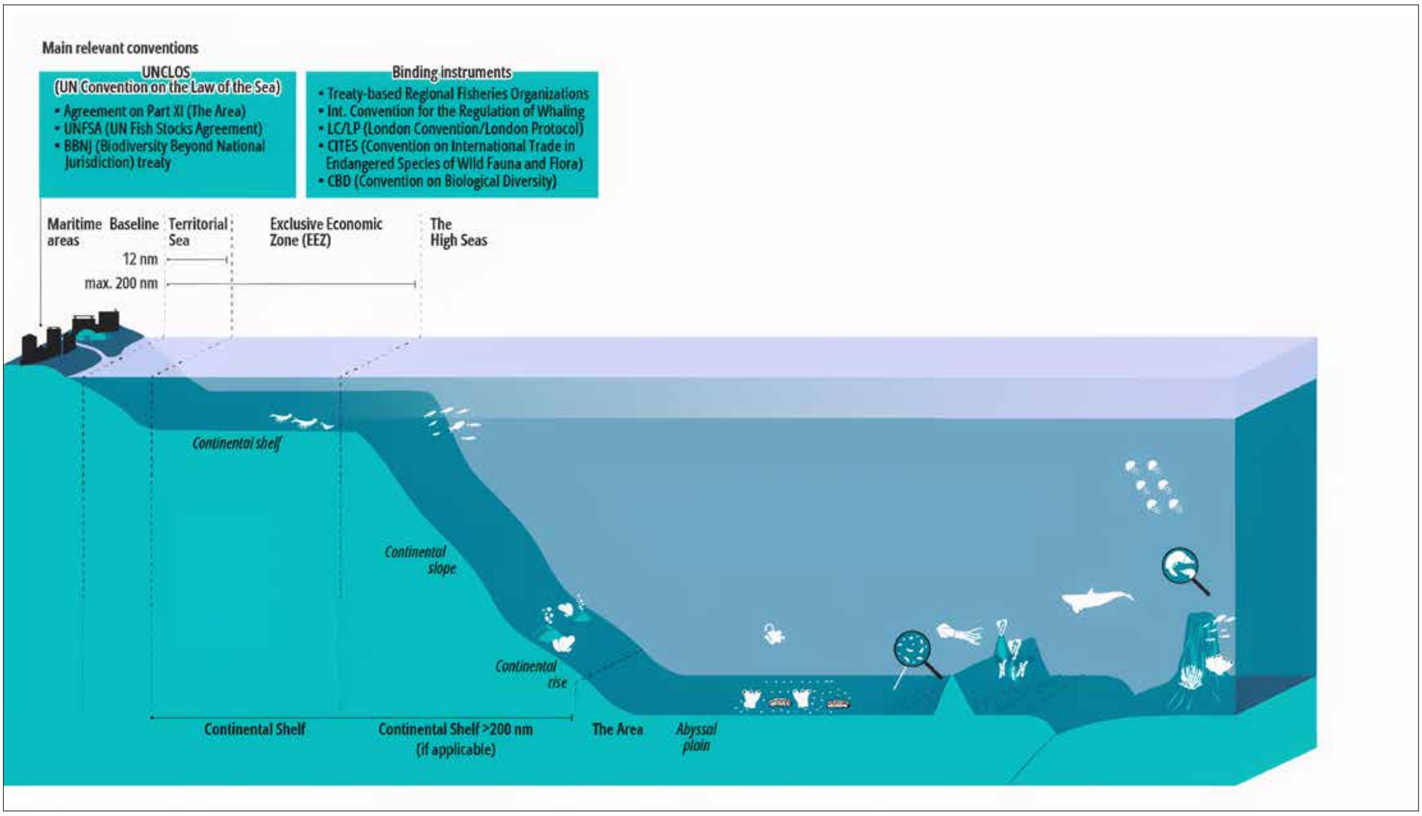
Credit: Andrés Alegría/ EMB

Figure 1.2 Water column zonation and the main geological features as well as associated habitat types in the deep sea based on natural sciences definitions. The Ocean is dynamic and interconnected, from the surface to the seafloor and from the coasts to the high seas through the active and passive movements of water masses, plants, animals, and the suspended particulate material.

Increasing knowledge of deep-sea ecosystems and technical progress have accompanied the development of maritime economic activities over many decades and paralleled the evolution of international law and the Law of the Sea. Since the 19th century, marine and maritime economic activities such as shipping, fishing, oil and gas extraction, and laying cables and pipelines, have grown considerably. Emerging activities, including deep-sea mining, marine Carbon Dioxide Removal (mCDR), and energy production, are being conducted or considered (see Chapter 5). Efforts to develop Ocean-based solutions for climate change mitigation and adaptation have recognised the Ocean as a sink and a reservoir of heat and greenhouse gases (GHGs), like carbon dioxide (CO_2). Ocean-Based Climate Interventions (OBCIs) to produce renewable energy, remove and sequester carbon dioxide, or manage solar radiation (marine Solar Radiation Modification, mSRM[2]) have accelerated, raising questions about costs, governance, impacts, and effectiveness at scale. However, limited attention has been given to the impacts of OBCIs on Ocean biogeochemistry and ecosystems, particularly in understudied deep-sea ecosystems, which are fundamental for the health of ecosystems on Earth (Levin et al., 2023) and where anthropogenic impacts can be seen down to the hadal zones (Peng et al., 2020). Certain OBCI techniques raise issues regarding the interaction with the global climate norms, rules and decision-making procedures (Guilloux, 2020) and could constitute a type of pollution of the marine environment as defined by the United Nations Convention on the Law of the Sea (UNCLOS (Art. 1.1.4)) (Proelss, 2022). States should take measures to prevent, reduce, and control the use of such technologies unless they comply with their obligations under international law (see Chapter 2).

1 Interactive global map with the maritime boundaries https://marineregions.org/eezmapper.php

2 SRM is a deliberate and large-scale intervention attempting to offset the effects of greenhouse gases by causing the Earth to absorb less solar radiation. An example is adding aerosols to the lower atmosphere over the Ocean to increase the reflectivity of low-lying marine clouds.



Credit: Andrés Alegría/EMB

Figure 1.3 Graphical representation of the various maritime areas, relevant institutions and conventions, in the water column and at the seafloor, in shallow marine waters and the deep sea (see Chapter 2 for further information and specific considerations).

The impacts of human activities on the marine environment are complex and varied (see Chapter 5). They can be direct or indirect, localised, or far-reaching. Long-term consequences, such as the decline of marine biodiversity, the expansion of plastic and chemical pollution, global warming, and Ocean acidification, are recognised by the international community and the United Nations (UN). Some impacts, such as Ocean warming, acidification and deoxygenation, are irreversible on a human timescale (IPCC, 2019), and the health of the Ocean is intimately linked to that of the deep sea (see Section 1.3).

The right to a healthy Ocean derives from international environmental law (e.g. UNCLOS, Convention on Biological Diversity (CBD), United Nations Framework Convention on Climate Change (UNFCCC)) and is anchored in the United Nations Decade of Ocean Science for Sustainable Development (2021-2030)[3]. It aligns with the right to a clean, healthy and sustainable environment recognised by the UN General Assembly[4], promoting a "human rights-based approach" to environmental protection[5]. The adoption of a systems-thinking approach to social and environmental change, where human, animal, other organisms', and ecosystem health are interconnected, supports the "One Health"[6] approach that goes beyond reinforcing the concepts of the ecosystem-based management (EBM) approach (O'Hagan, 2020). It transcends the spatial basis of ecosystem management to move towards a more dynamic approach. It reinforces the theory of the Rights of Nature as an imperative to preserve ecological integrity and to support global Ocean stewardship (Harden-Davies et al., 2020) and "One Health" concepts. These approaches concur with the principle of ecological solidarity (Rousso, 2019) and integrated approaches to Ocean management.

Despite the vast volume and importance of the deep sea, it remains largely unknown due to the relatively small number of experts compared to its huge extent, technological challenges and limited financial resources available for its study. Baseline data needed to understand, sustainably manage, and conserve its biodiversity are currently scarce and unevenly distributed globally (see Chapter 4). Understanding the deep sea and its role in Ocean health is challenging due to this lack of data, its remoteness and its complex legal landscape (see Chapter 2). The international scientific community and networks (e.g. Deep Ocean Stewardship Initiative (DOSI)[7], Deep Ocean Observing Strategy (DOOS)[8], International cooperation in Ocean floor studies (InterRidge)[9], Scientific Committee on Oceanic

[3] https://oceandecade.org/

[4] United Nations General Assembly (UNGA) The human right to a clean, healthy and sustainable environment (2022) UN Doc A/RES/76/300 https://documents.un.org/doc/undoc/gen/n22/442/77/pdf/n2244277.pdf

[5] OHCHR, UNEP and UNDP Information Note "What is the Right to a Healthy Environment?" https://www.undp.org/sites/g/files/zskgke326/files/2023-01/UNDP-UNEP-UNHCHR-What-is-the-Right-to-a-Healthy-Environment.pdf

[6] The concept of "One Health" gained formal recognition in various international organisations (World Health Organization (WHO), the Food and Agriculture Organization (FAO), and the World Organisation for Animal Health (WOAH) in the early 2000s, driven by increasing awareness of emerging infectious diseases (H5N1 avian influenza, SARS, and H1N1 influenza) and, reached its peak with the COVID-19 pandemic.

[7] https://www.dosi-project.org/

[8] https://www.deepOceanobserving.org/

[9] Since 2024, InterRidge is no longer active

Research (SCOR)[10], Deep-Sea Biology Society (DSBS)[11]), along with intergovernmental bodies (e.g. International Seabed Authority (ISA)[12], Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO)[13], International Union for Conservation of Nature (IUCN)[14]), civil society NGOs (e.g. High Seas Alliance[15], Deep Sea Conservation Coalition[16], World Wildlife Fund (WWF)[17], Greenpeace[18]) and private foundations (e.g. Schmidt Ocean[19], Foundation Tara Ocean[20]), share their knowledge and/or advocate for deep-sea protection and effective management to policymakers at national and international levels. Still, due to a general lack of Ocean literacy, deep-sea stakeholders, and the public in general, are often unaware of the deep sea's vital role in Earth's functioning and human livelihoods (see Section 1.3).

1.2 The Ocean is connected, from the shore to the greatest depths

The deep sea interacts with the entire Ocean system and is influenced by processes involving the lithosphere (the Earth's crust and mantle), atmosphere (the Earth's thin gas layer), cryosphere (the Earth's frozen water), hydrosphere (the Earth's water system), and biosphere (all of Earth's living beings and ecosystems). The Ocean connects the marine environment from the shore to the greatest Ocean depths, i.e. the “Challenger Deep”[21].

Connectivity describes the ecological linkages between autotrophic (primary producers like plants, algae, and microbes) and heterotrophic organisms (consumers like animals, fungi, and microbes) and their physical environment across scales from micrometres to thousands of kilometres. Major vertical connections — from the surface to thousands of metres deep — include the sinking of marine snow/particles, transporting carbon and energy to the deep seafloor, and large-scale thermohaline circulation, which drives Ocean mixing (deep-sea convection) through temperature and salinity differences in seawater. Ocean currents transport heat, oxygen, and nutrients, and move non-living and living particles, including plankton.

Biological movements can be passive, such as those of many plankton species, or active, like those of swimming fish, mammals, or turtles. Active movements occur at various spatial and temporal scales, horizontally and vertically. Daily vertical migrations, the largest and most frequent biological movement on Earth, allow mesopelagic fauna (at 200 m - 1,000 m depth), including zooplankton and other small organisms able to swim independently of Ocean currents (or nekton), to exploit the high productivity in the epipelagic zone (0 - 200 m depth) at night while avoiding visual predators during the day (see Figure 4.3). Migrating mesopelagic fauna serve as food for exploited and charismatic species, such as fish and whales (Iglesias et al., 2023), which travel across the Ocean to feed and breed. Some pelagic organisms, such as “Dumbo” octopuses, migrate to the seafloor to feed (Golikov et al., 2023), whilst many benthic species (species living in and on the seafloor) have pelagic larvae that disperse via Ocean currents.

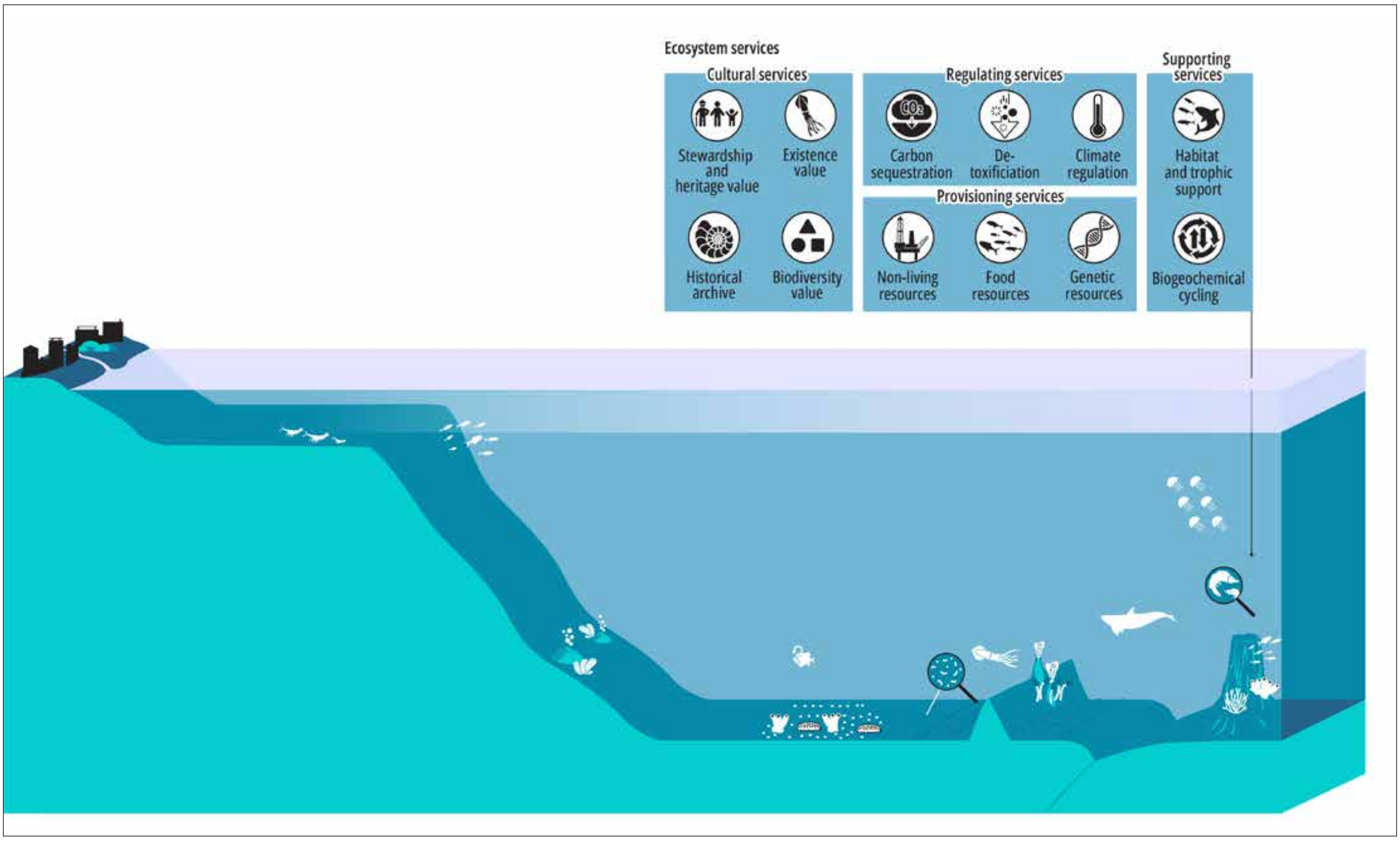
These biological and physical connections are critical for maintaining Ocean ecosystem functions such as the capture of “blue carbon”. Between 0.1 - 2% of the primary production in surface waters reaches the deep seafloor, where it sustains deep-sea benthic communities and sequesters carbon into the sediment (Smith et al., 2008). Pelagic organisms play crucial roles by transporting carbon absorbed by phytoplankton to the deep seafloor, where it is reworked by benthic organisms and it can be stored on geological timescales. This process is known as the “Biological Carbon Pump” (BCP), see Figure 4.2, Section 4.1.2, and the EMB Policy Brief on Blue Carbon provides more information on the BCP (European Marine Board, 2023).

1.3 The deep sea provides critical ecosystem services and functions for our planet

Although ~90% of the Ocean is considered deep sea, this vast area and volume is often overlooked (DOSI, 2022). The deep sea provides a wide range of supporting, provisioning, regulating, and cultural ecosystem services that benefit humankind and all forms of life (see Figure 1.4).

Deep-sea supporting services include nutrient cycling, primary production without sunlight (or chemosynthesis), secondary production, and the presence of biologically mediated habitats formed by marine organisms (La Bianca et al., 2023). The deep sea offers crucial climate regulating services through the heat and carbon pumps, acting as the largest active and natural sink and reservoir of GHGs through the biological and physical carbon pumps (see Figure 4.2; European Marine Board, 2023). Often referred to as the “lung of our planet”, the Ocean produces over 50% of the Earth's oxygen (see EMB Future Science Brief on Ocean oxygen, Grégoire et al., 2023). The seafloor, dubbed the “liver of our planet”, sequesters several gigatons of CO_2 annually, with biotic-mediated processes promoting its transfer, from the atmosphere to the deep sea (Wang et al., 2023). Additionally, the Ocean regulates the planet's temperature by absorbing up to 90% of the excess heat trapped by GHGs (von Schuckmann et al., 2023). Model-based

10 https://scor-int.org/
11 https://dsbsoc.org/
12 https://www.isa.org.jm/
13 https://www.ioc.unesco.org/en
14 https://iucn.org/
15 https://highseasalliance.org/
16 https://deep-sea-conservation.org/
17 https://www.worldwildlife.org/
18 https://www.greenpeace.org/international/
19 https://schmidtOcean.org/
20 https://fondationtaraOcean.org/
21 The deepest part of the Ocean is called the Challenger Deep (10,984 m) and is located in the western Pacific Ocean on the southern end of the Mariana Trench.



Credit: Andrés Alegría/ EMB

Figure 1.4 Graphical representation of the various ecosystem services which are provided by the deep sea.

analysis suggests that 35% of that excess heat is being taken up in the deep sea (Gleckler et al., 2016).

In addition to the important provisioning service of food from the Ocean, with 17% of global animal protein harvested coming from the sea (Costello et al., 2020), the deep sea holds an incredible wealth of marine genetic diversity (marine genetic resources, or MGR; Rogers et al., 2021) awaiting discovery, research, and development (Rogers et al., 2015). These genetic adaptations, chemical compounds, and biomaterials have potential applications in pharmaceuticals and industrial processes (Guilloux, 2018). Digital Sequence Information (DSI) of MGRs offers direct and indirect benefits, including biodiversity knowledge, conservation, bioremediation, and knowledge on the adaptability of marine organisms to climate change. In addition, marine biomimetics and inspiration from the deep sea offer substantial monetary benefits (Blasiak et al., 2022).

Deep-sea cultural services, which are difficult to quantify and therefore often overlooked, include knowledge systems and educational values, cultural diversity, aesthetics and inspiration for the arts, and spiritual or religious values (La Bianca et al., 2023). Indigenous knowledge, i.e. the knowledge, innovations and practices developed from experience gained over the centuries and adapted to the local culture and environment (DOSI, 2021), can be collectively owned and passed down through millennia, as for example in communities in the Pacific Islands. It comes in the form of stories, songs, chants, folklore, proverbs, dances, paintings, cosmologies, cultural values, beliefs, rituals, community laws, local language, and practices in which the deep sea is part of a whole (DOSI, 2021). While we recognise the significance of deep-sea cultural services—including knowledge systems, educational values, cultural diversity, aesthetics, artistic inspiration, and spiritual or religious connections—this report could not explore these aspects in detail, due to the predominantly marine natural science focus of the Working Group.

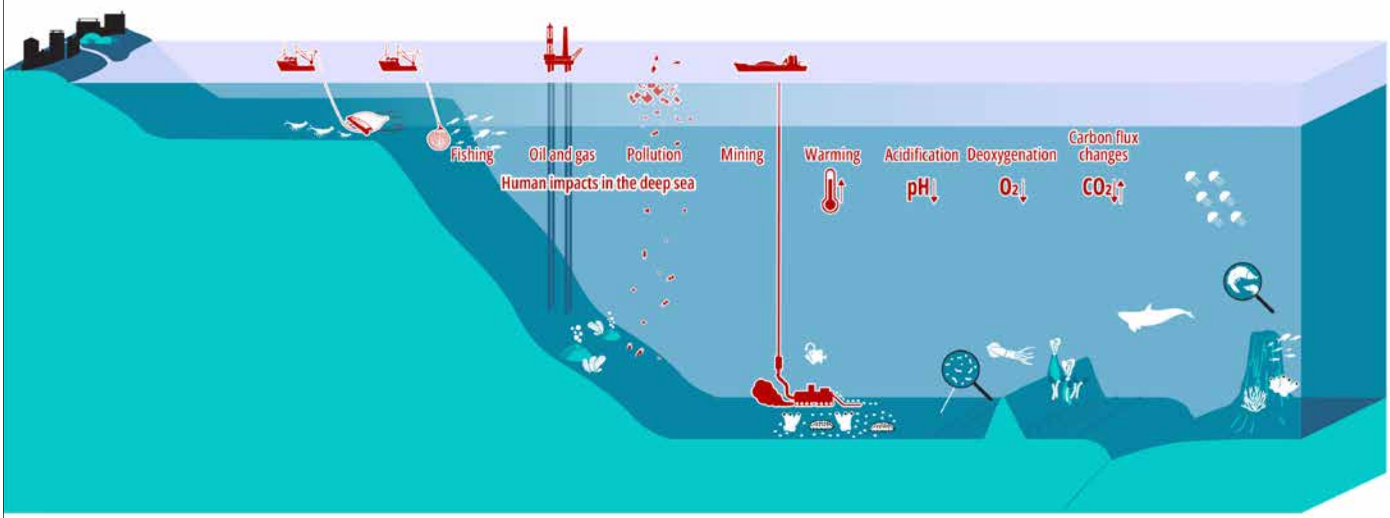
The deep sea is thus critical to all our lives, providing numerous services. Changes to the deep sea, and especially those affecting regulatory services, could have a global impact. Identifying and understanding critical ecosystem functions, their locations, and their connections with the different depth realms and ecosystems of the Ocean, is imperative. This knowledge is essential to determine what requires protection and where to ensure that humanity continues to benefit from a healthy and functioning Ocean. Any risks and costs associated with future use of the deep sea must be carefully evaluated, considering potential negative effects on natural ecosystem services and functions, with potential spill-over effects on the rest of the Ocean and the wider Earth system.

1.4 (Deep) Ocean health is at risk

The deep sea is currently at risk from various human impacts (Figure 1.5 and Chapter 5). Due to the interconnectedness of Ocean layers, changes in the upper Ocean also impact deep-sea ecosystems. The deep sea absorbs substantial amounts of heat and CO_2 originating from anthropogenic CO_2 emissions (Cheng et al., 2020; IPCC Chapter 5, 2019). The absorption of heat and CO_2 in the deep-sea buffers climate change but exposes vulnerable deep-sea ecosystems to warming, changing currents, acidification, deoxygenation, and altered food input (see Section 5.1).

In addition, overexploitation of renewable resources such as fish, and of non-renewable resources such as oil, gas (energy) and minerals, can cause significant habitat deterioration, biodiversity loss and ecosystem function collapse (see Section 5.2; IPCC, 2014). Anthropogenic pollution, including noise, chemicals, pharmaceuticals, and plastics, reaches the deepest parts of the Ocean (Peng et al., 2018; Ferreira et al., 2022). All these human activities have intensified throughout history and are now reaching tipping points in the Anthropocene (Gaffney & Steffen, 2017). Many new activities, which are currently only at the research and development stage, such as bioprospecting (the search for and commercialisation of new products derived from nature), the use of marine genetic resources, renewable energy production, deep-sea mining and OBCIs, present risks and/or ethical concerns (see Section 5.3). A strong regulatory and institutional framework, based on the rule of law and science-based evidence, needs to be implemented to address the transnational and global issues of deep-sea use.

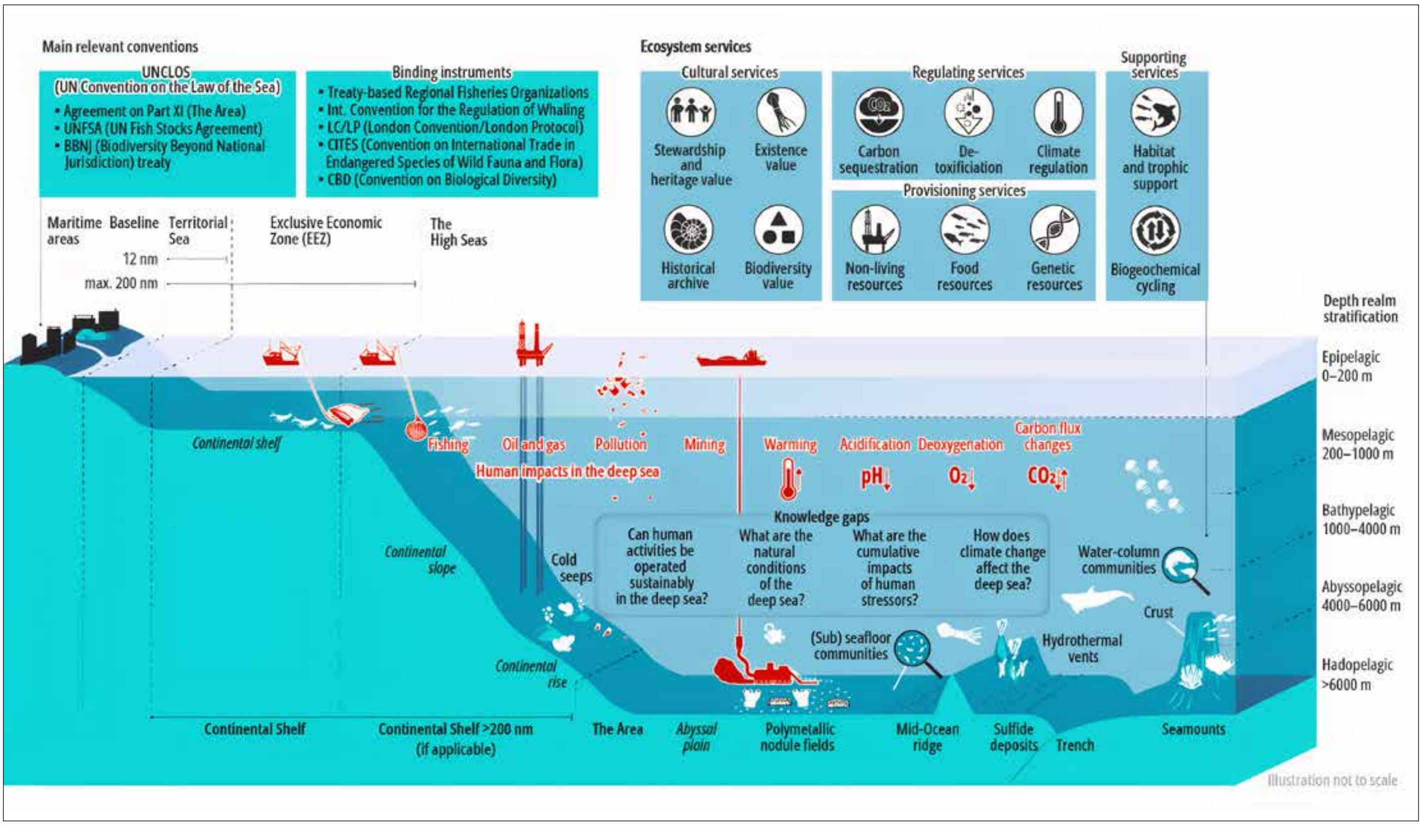
Despite the deep sea's significant role in global processes and the major threats it faces, scientific knowledge gaps currently hinder informed decision-making and sustainable management (see Chapter 4). Critical resource exploitation, such as deep-sea mining, may soon become a reality[22], yet there is insufficient scientific knowledge for effective environmental management of these activities (Amon et al., 2022). Gaps in understanding deep-sea physical, biogeochemical, and biological processes also limit our ability to monitor and respond to climate change (DOSI, 2023), even though there is a clear scientific consensus on the Ocean's central role in climate regulation. Efforts to remove atmospheric carbon within the Ocean and sequester it at depth (mCDR) are of undeniable economic interest, but the long-term efficacy and consequences of these techniques for marine ecosystems remain unknown (Levin et al., 2023; see also Section 5.3). Independent operational monitoring systems for open-Ocean mCDR deployments to detect, attribute, and assess the side effects of such implementations are being suggested (Boyd et al., 2023). An EMB document on monitoring, reporting and verification of mCDR approaches is currently in preparation[23]. To make informed decisions on the use and non-use of the deep sea and to prevent harmful effects on the marine environment and loss of ecosystem functions and services, it is essential to understand the potential impacts of all current and future uses on the deep sea.



Credit: Andrés Alegría/ EMB

Figure 1.5 Graphical representation of ongoing and potential future human impacts on the deep sea.

[22] https://www.regjeringen.no/en/aktuelt/public-consultation-of-the-first-licensing-round-for-seabed-minerals/id3047008/
[23] https://www.marineboard.eu/marine-carbon-dioxide-removal



Credit: Andrés Alegría/ EMB

Figure 1.6 Summary of geological features, biological communities, ecosystem services, human impacts, institutions and conventions related to the deep sea, together with the main knowledge gaps. More systematic, proactive, and long-term approaches to protect the marine environment and manage its resources based on scientific evidence are needed.

1.5 2025: Time to take action for Ocean Health

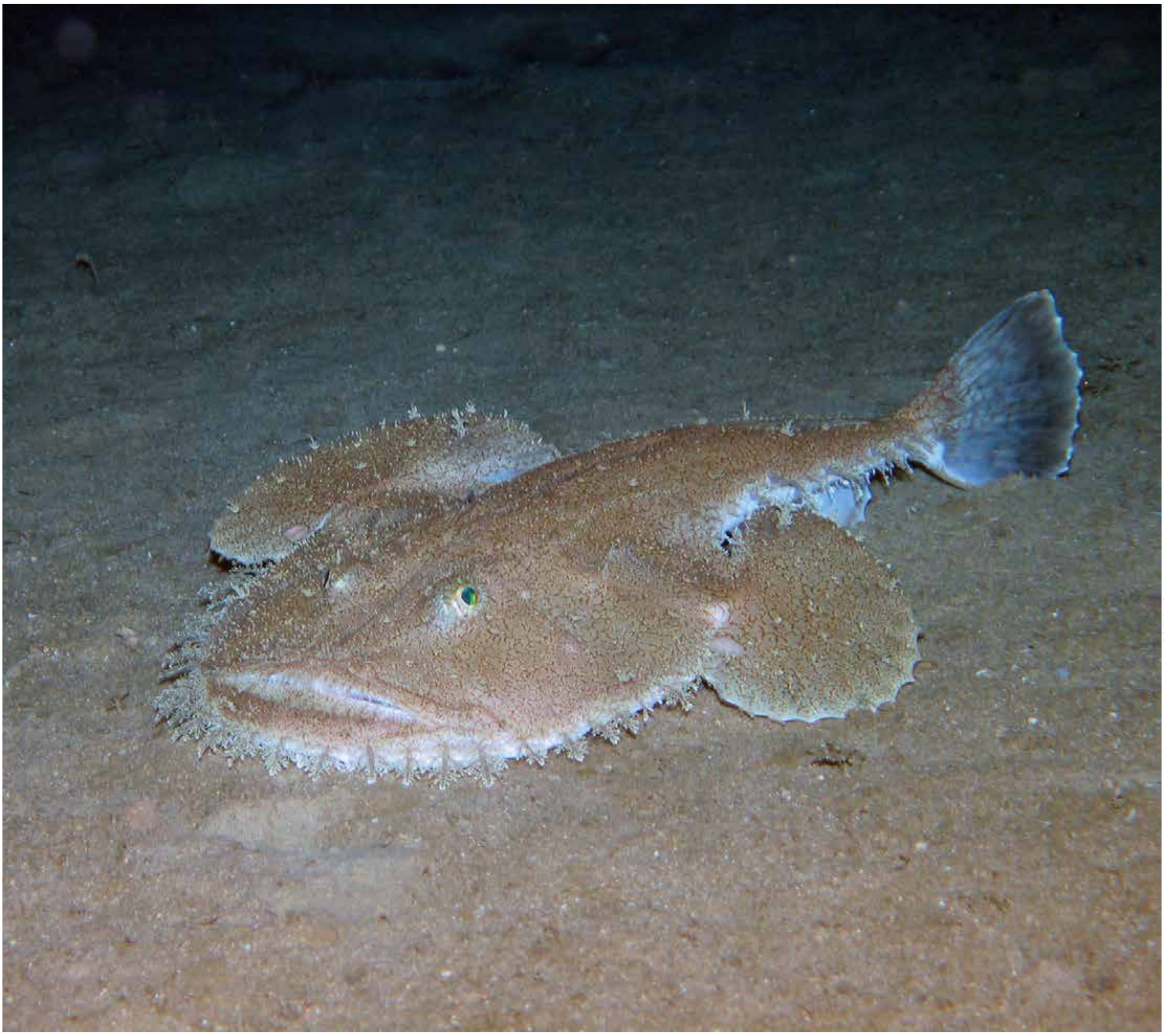
Deepening the understanding and respect for the environment is critical now and for the next decades to effectively address climate change and achieve net zero emissions by 2050[24]. Climate change is one of the most concerning threats to human and biosphere integrity, and alongside biodiversity loss it could lead to major and irreversible disruptions of the Ocean and the cryosphere in the near future (IPCC, 2019). The rapid entry into force of, and universal commitment to the 2023 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 (BBNJ Agreement) (see Section 2.6) are essential for the integrated and effective management of marine biodiversity. Strong alignment between the different regulations and regularity bodies, for example the BBNJ Agreement and the ISA legal documents, is needed. It is also essential to significantly improve scientific understanding of the world's largest biome and to build transdisciplinary bridges to identify and address the socio-ecological issues that prevent the achievement of a healthy and resilient Ocean for all, in line with the Sustainable Development Goals and the UN Ocean Decade. Efforts to increase collaboration for advancing deep-sea science under the UN Ocean Decade have highlighted several objectives in line with the recommendations in this document (see Chapter 6), such as identifying and characterising deep-sea ecosystem vulnerability and resilience to climate change, climate intervention, and resource extraction; and enabling a multidisciplinary, collective, deep-sea observing system (Hetherington et al., 2024).

In 2015, the European Marine Board published Position Paper N° 22 "Delving Deeper: Critical challenges for 21st century deep-sea research" (Rogers et al., 2015), followed by the accompanying Policy Brief 2 "Delving Deeper: How can we achieve sustainable management of our deep sea through integrated research?" (Larkin et al., 2015). These publications provided a comprehensive overview of the knowledge and research requirements, policy gaps and societal needs that exist for deep-sea regions, their ecosystems, their management, and their governance, at the time of writing. In addition, the relevance of this knowledge in the context of growing industrial interest and pressure from Blue Economy sectors was stressed.

Since 2015, a significant body of knowledge has been gathered regarding the deep sea, its inhabitants and ecosystems, how they connect, and how they are or may be impacted by human activities. However, many of the gaps that were highlighted in 2015 have not yet been filled (Chapter 4). Studies often focus on limited regions, parameters or species, and disciplines. Broader and more integrated perspectives are still lacking. Recent legal and policy developments, such as the 2023 BBNJ Agreement and political calls for a ban, moratorium, or precautionary pause on deep-sea mining, reflect a movement towards more systematic, proactive, and long-term approaches to protect the marine environment and manage its resources based on scientific evidence.

[24] §28 d, Outcome of the first Global Stocktake, Proposal by the President Draft decision/CMA.5, Doc FCCC/PA/CMA/2023/L.17, 13 December 2023, https://unfccc.int/sites/default/files/resource/cma2023_L17_adv.pdf

As diverse interests converge on the deep sea, it is important to identify and close knowledge gaps and turn knowledge into action (Figure 1.6). This document explains the complex legal landscape regarding the deep sea (Chapter 2), addresses the challenges of studying the deep sea (Chapter 3), the main knowledge gaps in understanding the deep sea and Ocean health (Chapter 4), the main environmental and societal issues impacting the deep sea (Chapter 5) and general recommendations to improve deep sea and Ocean health (Chapter 6).



Anglerfish at a depth of 320 m in the western Mediterranean Sea. Identifying and characterising deep-sea ecosystem vulnerability (to, for instance, overfishing or bycatch) and resilience to climate change are critical now and for the decades to come.

2 The complex legal landscape of the deep sea

2.1 Lack of legal definition of the “deep sea”

Although the terms “deep sea”, “deep Ocean” and “deep seabed” are widely and sometimes interchangeably used in legal discourse and literature, the “deep sea” is not universally defined. The 1982 United Nations Convention on the Law of the Sea (UNCLOS) does not address the deep sea on its own[25]. As a "living instrument" UNCLOS does not confine the deep sea to a static or narrow definition but embraces an evolving approach based on science and changing economic, social, or technical circumstances.

Despite not being defined, there are several provisions in UNCLOS which apply to the deep sea. States collectively and individually have the obligation to protect and preserve the marine environment, which includes the "deep sea" (Part XII UNCLOS). Similarly, States must protect and preserve "biodiversity" more stringently when rare, vulnerable or at risk (Art. 194(5) UNCLOS), as well as conserve and sustainably use (Part V UNCLOS, Art. 1 of the Convention on Biological Diversity (CBD) and Art. 2 BBNJ) deep-sea life. "Extractive" human activities in the deep sea, i.e. below 200 m, such as bottom fishing or offshore oil and gas drilling, and mineral extraction, also fall within the general scope of application of UNCLOS. The same applies to new maritime activities linked to the deep sea, within national jurisdiction (generally the Exclusive Economic Zone (EEZ) and continental shelf) or beyond (High Seas, the Area, see Figure 1.3), some of which are already subject to specific regulations in accordance with UNCLOS and other relevant international instruments (e.g. Ocean fertilisation under the London Protocol)[26].

2.2 Spatial division of the Ocean: areas within and beyond national jurisdiction

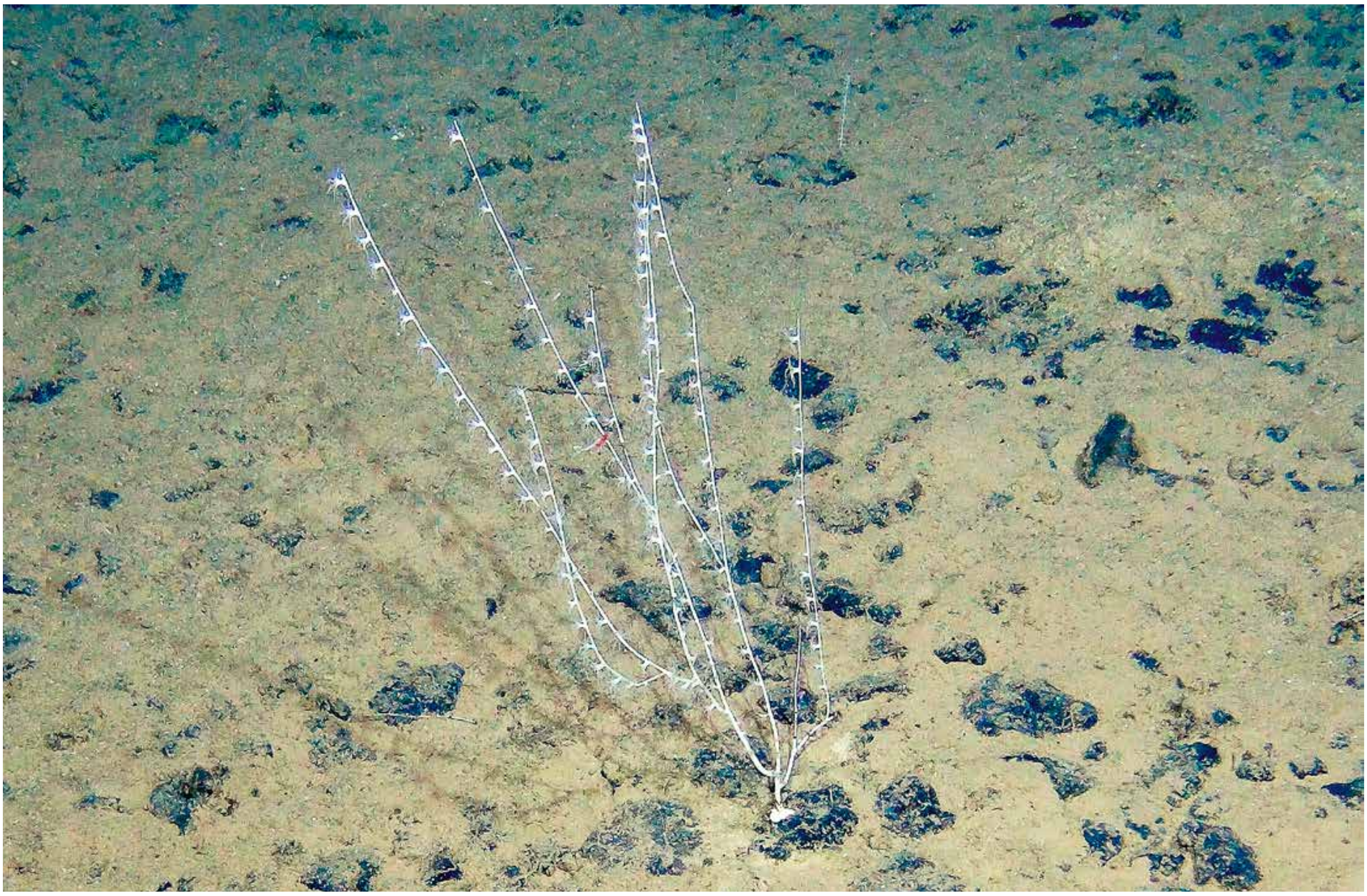
The "legal landscape" of the deep sea is complicated and fragmented, because of the division of the marine environment into maritime areas, and the distribution of competences between States over living and non-living resources, maritime activities, and the marine environment. Depending on the geographic location, maritime areas encompassing parts of the deep sea may lie within or beyond national jurisdiction. UNCLOS allows States to extend their national jurisdiction by proclaiming an EEZ of up to 200 nautical miles from the coast and/or claim an extended continental shelf of up to 350 nautical miles or 100 nautical miles from the 2500 m isobath, whichever is most seaward (Art. 76 (5) and (6) UNCLOS). While the EEZ regime (Part V) is based on the exclusive rights of coastal states over natural resources, particularly living resources, the regime of the continental shelf (Part VI) gives them sovereign rights to explore and to exploit mineral resources and sedentary species (Art. 77(4)).

Areas Beyond National Jurisdiction (ABNJ), including the “High Seas” and “the Area”, represent around 64% of the surface of the Ocean, and include a wide range of unique ecosystems. Although the deep-sea environment of these areas falls under "the Commons" that are of common use and internationally managed, legal principles applicable to the seabed (or “the Area”) and the water column (or “High Seas”) are very different. On the “High Seas” (i.e. all parts of the sea that are not included in an EEZ, territorial sea, or internal or archipelagic waters of a State), deep-sea biodiversity, whether living or genetic resources (different in a legal context), is freely accessible under the qualified principle of freedom (Art. 87 UNCLOS), provided that certain obligations are met (e.g. obligations under UN Fish Stock Agreement). In contrast, “the Area” (i.e. the seabed and Ocean floor and subsoil thereof (Art. 1(1) UNCLOS)) and its resources cannot be the subject of any exclusive right or appropriation (Art. 133 and 137 UNCLOS) because it is defined in UNCLOS as the Common Heritage of Mankind (CHM).

Although the legal focus of UNCLOS has been on activities related to mineral resources (research, exploration, prospection, exploitation), the CHM is a guiding principle in achieving the objectives of the BBNJ Treaty (Art. 7 BBNJ), whose scope is effectively expanded to encompass ABNJ (Art. 3 BBNJ). This could be interpreted to apply to the activities conducted by States in the water column (in ABNJ). The Area falls under the mandate of the International Seabed Authority (ISA) (Part XI UNCLOS, 1994 Agreement and Mining code), but until all States have fixed the outer limit of their continental shelf pursuant to UNCLOS, the Area cannot be precisely delineated (Churchill et al., 2022).

[25] UNCLOS approaches the deep sea in regard to “the Area's" (the seabed, Ocean floor and subsoil thereof) legal status of Common Heritage of Mankind (Part XI UNCLOS, 1994 Agreement and Mining code) under the mandate of the International Seabed Authority (ISA). The margin of the continental shelf thus does not include the “deep Ocean floor” with its ocean ridges or the subsoil thereof, as defined according to geology (Art. 76.3 UNCLOS; see Figure 1.3).

[26] https://www.imo.org/en/OurWork/Environment/Pages/OceanFertilization-default.aspx



Soft coral growing on top of a manganese nodule in the central Pacific Ocean. The ecological diversity in deep-sea plains is enormous, especially where manganese nodules cover the seabed. These mineral resources on "the Area" are the common heritage of mankind.

2.3 Legal rules and competences of EU Member States on deep-sea matters

The EU context illustrates the diversity and complexity of legal rules applicable to the deep sea of Member States (MS) and beyond national jurisdiction. Of the 27 EU Member States, 24 have maritime territories of varying size [27]. The division of competences between the EU and its MS varies according to the subject matter. Competences in the areas of environmental policy, fisheries, and maritime affairs are shared between MS and the EU. However, areas closely tied to State sovereignty, such as the exploitation of mineral resources of the continental shelf or decision-making power at the ISA, remain primarily the competence of the MS. This is key to understanding the position of the European Parliament and Commission on deep-sea mining, which may contrast with the policies of individual MS (Singh et al., 2023).

2.4 UNCLOS: Holistic approach to the marine environment

UNCLOS is often referred to as the "constitution for the Oceans"[28] because it adopts a holistic approach to the entire marine environment. Apart from Part XI ("the Area"), most provisions related to the marine environment applicable to the deep sea are found in Part XII on the "protection and preservation of the marine environment". States have the general obligation to protect and preserve the whole marine environment. This treaty obligation, which is also customary in nature, is further specified through a set of provisions on measures to prevent, reduce and control pollution of the marine environment from different sources (Art. 194 and seq.).

The systemic approach is rooted in several principles of public international law. These principles are either recognised or emerging in UNCLOS and other relevant instruments in the fields of environmental protection or human rights, guiding the conduct of states in due diligence and good faith. This comprehensive approach includes principles such as cooperation, the human right to science, the qualified principle of freedom of the High Seas and of scientific research, the CHM, the prevention of harm principle, the precautionary principle or approach, and ecosystem-based and integrated approaches to Ocean management.

[27] States such as France have immense maritime and deep-sea territories in different parts of the Ocean relating to their overseas territories, while others such as Malta have limited maritime territories with no deep sea.

[28] Speech by Koh, T. T. B. (1982). 'A Constitution for the Oceans'. Remarks by the President of the third Conference on the Law of the Sea. 5p. https://www.un.org/depts/los/convention_agreements/texts/koh_english.pdf

The holistic approach to the marine environment in UNCLOS is further supported by the jurisprudence and advice of independent bodies, and it is reinforced in "soft laws". For instance, the International Tribunal for the Law of the Sea (ITLOS) is an independent body established by UNCLOS to address questions or disputes arising from the interpretation and application of the Convention. In its advisory opinion of 21 May 2024 on the obligations of States in combating the effects of climate change on the marine environment (Case N° 31) the twenty-one ITLOS judges unanimously decided that anthropogenic GHG emissions constitute pollution of the marine environment, including implicitly the deep sea, within the meaning of Art. 1(4) UNCLOS. The holistic approach is also included in the best available science on the Ocean within the Earth system, as provided by scientific processes such as the Intergovernmental Panel on Climate Change (IPCC), World Ocean Assessment (WOA) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). Finally, the holistic approach is reinforced by the "soft law" concepts of Ocean health (UN Ocean conferences, World Ocean Index) and SDG 14 (Life below water).

2.5 Legal fragmentation

UNCLOS is not isolated: it exists within a complex framework of international, regional, and national rules, procedures, standards, and organisations that elaborate on its general obligations. Numerous relevant international legal rules, both binding and non-binding, address many aspects such as environmental protection, maritime safety, maritime security, and fisheries, and sectors like shipping under the International Maritime Organization (IMO) mandate. As a consequence, global, regional and sectoral bodies and coastal states develop policies and laws for different sectors and regimes such as shipping, dumping, fishing, oil and gas extraction, deep-sea mining, climate change, environment and conservation (Figure 2.1). Globalisation has fostered greater uniformity in social life and law worldwide, but it has also led to increased fragmentation, questioning the coherence and cooperative nature of international law and governance. Incoherence and lack of cooperation emerged from specialised law-making and relatively autonomous legal rules, regimes (e.g. climate change, biodiversity, food security), institutions (e.g. Convention on Biological Diversity (CBD), regional fisheries management organisations (RFMOs), etc.), and spheres of legal practice, with relative unawareness of legislative and institutional activities in the adjoining fields (Koskenniemi, 2006). In addition to the blurred distinction between the water column and the seabed, the different regimes between the Area and the continental shelf furthermore complicates our understanding and management of the deep sea. Rather than a threat, the fragmentation of international law can be seen as an opportunity, making cognitive, technical, normative and institutional interactions between regimes increasingly likely (Van Asselt, 2014).

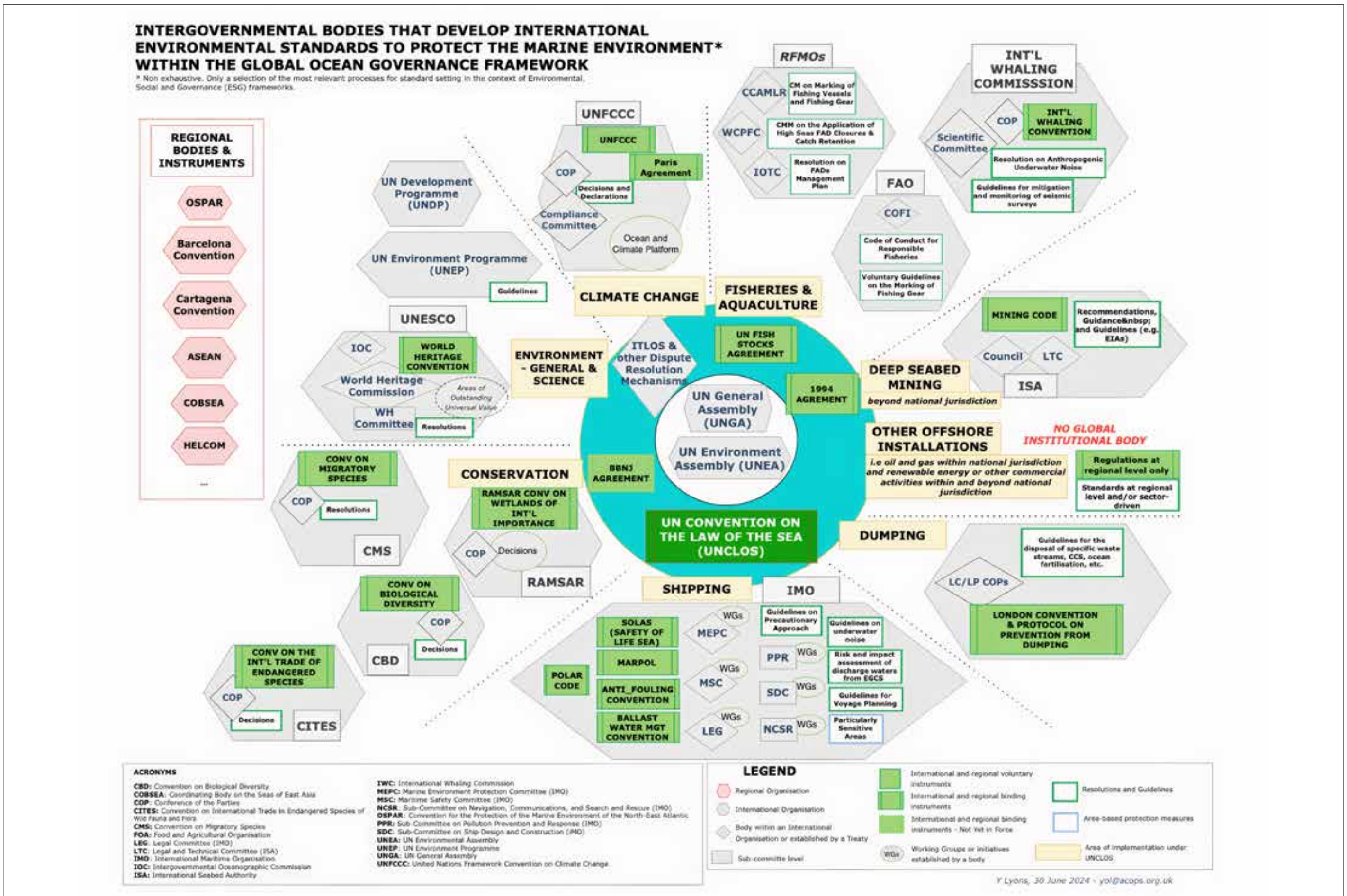


Figure 2.1 Non-exhaustive list of Intergovernmental bodies that develop international environmental standards to protect the marine environment within the global Ocean governance framework.

2.6 The Agreement on Marine Biodiversity of Areas Beyond National Jurisdiction (BBNJ Agreement)

For a long time, the biodiversity on the High Seas and in the Area, as well as the promotion of marine scientific research, have been subjected to an unprecedented double tragedy. The first, the "tragedy of the commons" (as suggested by Hardin, 1968), encapsulated by the collapse of fisheries, is linked to the over-exploitation of living resources and the erosion of marine biodiversity due to human activities. The second is a "tragedy of the anticommons" (Heller, 1998), arising from challenges in accessing knowledge, particularly from remote environments, where fragmented ownership rights and intellectual property protection restrict access and utilisation of the knowledge. This has led to research and development outcomes benefiting mainly developed states with greater financial resources and capabilities. This is illustrated by the number of patents associated with marine genetic resources, sometimes derived from simple discoveries in principle unpatentable (Guilloux, 2018) and held by an oligopoly of companies (Blasiak et al., 2018).

The Agreement under UNCLOS on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement) aims to address the decline in marine biodiversity in ABNJ, which includes most of the deep sea. After a long and complex political and diplomatic process, multilateral negotiations were successfully concluded in early 2023, and on 19 June 2023 the Agreement was adopted by consensus at the fifth BBNJ Intergovernmental Conference in New York. To date, the BBNJ agreement has been signed by more than 100 parties, including the EU (signed on 20 September 2023 by the President of the European Commission, Ursula von der Leyen). Signing expresses the willingness of the signatory State or party to continue the treaty-making process and for it to proceed to ratification. Signing also creates an obligation to refrain, in good faith, from acts that would defeat the purpose of the Treaty. Following signature, States can ratify the Agreement at any time. Ratification is when a State formally consents to the new international law, and this often entails ensuring that their national laws are consistent with the Treaty.

The BBNJ Agreement marks a historic landmark in how humans aim to manage interactions with the Ocean and the deep sea. It reflects a change in thinking about marine life, and recognises the importance of marine biodiversity, its functions (goods and services), and the necessity to monitor and enhance health impacts (Art. 17(c); Art. 31(b); Art. 35). While the connection between maritime areas is mostly implicit in UNCLOS, the BBNJ Agreement explicitly addresses ecological connectivity, which is one of the indicative criteria for identifying management areas, including Marine Protected Areas (MPAs; Annex I (m) of the BBNJ Agreement).

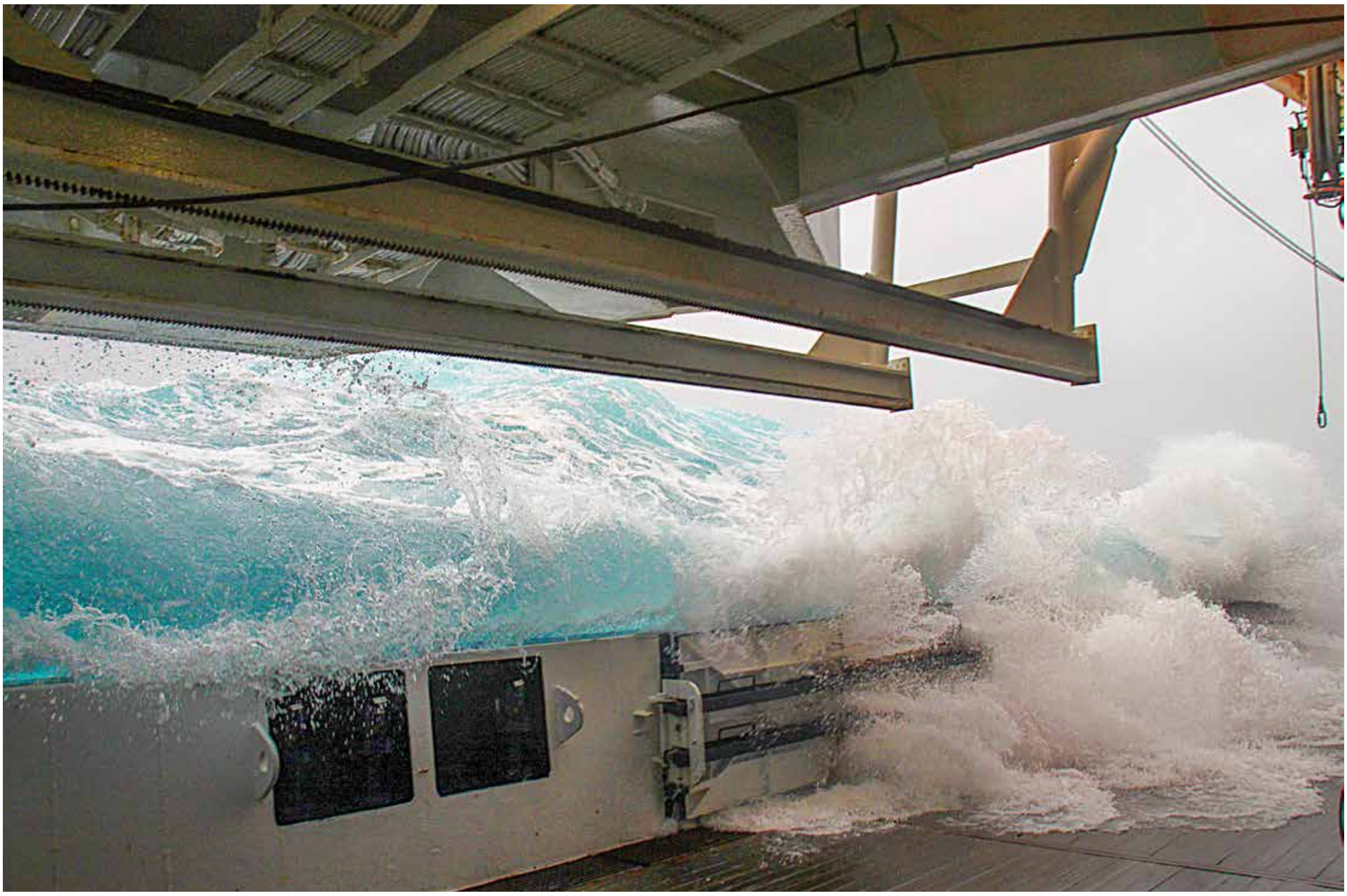
The BBNJ Agreement has the potential to act as a crucial milestone for States to be able to conserve and sustainably use marine biodiversity beyond national jurisdiction (Art. 2). To this end, the Agreement establishes specific rules governing: (1) access and fair and equitable sharing of benefits arising from activities with respect to Marine Genetic Resources (MGRs) and Digital Sequence Information (DSI) on MGRs; (2) area-based management tools including MPAs; (3) Environmental Impact Assessments (EIAs); and (4) capacity building and the transfer of marine technology. The BBNJ Treaty needs at least 60 ratifications before entering into force. However, although 110 States (including the EU) have signed the BBNJ Treaty by February 2025, only 17 states are party to the Agreement[29]. The success or failure of the BBNJ Agreement will depend on the commitment and action-taking of the UN Member States. The implementation of the agreement will require not only strong domestic laws and policies but also effective international cooperation.

[29] https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXI-10&chapter=21&clang=_en

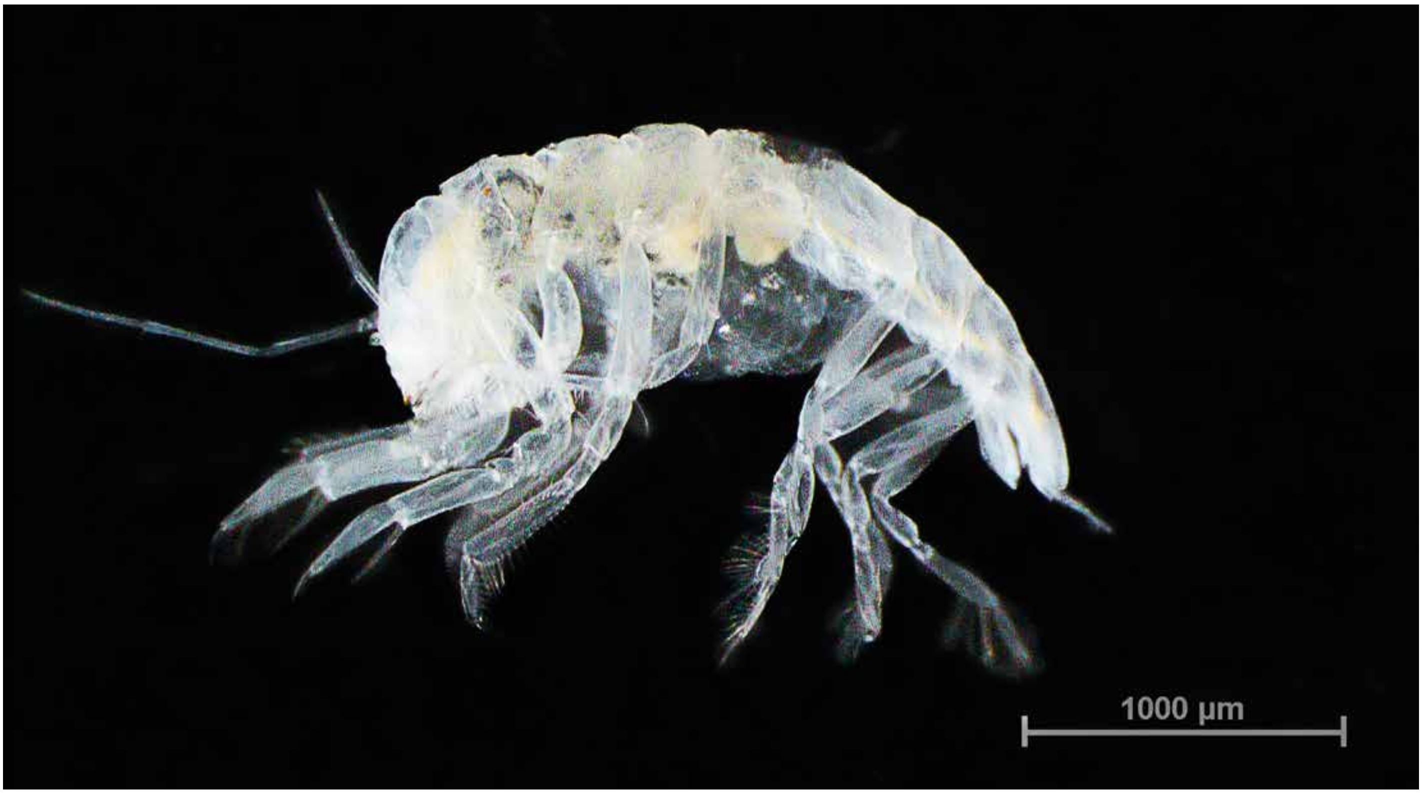
3 Challenges of studying the deep sea

Many important deep-sea processes are slow and still poorly understood, as access to the deep sea is logistically and technologically challenging and thus expensive, owing to its remoteness, vastness and, by definition, great water depth (Lins et al., 2021). Collecting scientific baseline data, or data for environmental impact studies, typically requires specialised vessels, expensive research equipment (see Box 1), and trained personnel to work for weeks to months at sea (Clark et al., 2016). The multidisciplinary nature of these expeditions, with several teams sharing ship time, samples and data, practically restricts the amount of data and samples that can be obtained from each deep-sea expedition. Moreover, the temporal and spatial extent of high-resolution deep-sea research is often limited by the tools available on board, due to cost, deck space, available operators and ship time. More information on deep-sea research capacity in Europe can be found in the EMB Position Paper on the Next Generation European Research Vessels (Nieuwejaar et al., 2019).

Deep-sea focused research campaigns often only provide snap-shots of the deep-sea environment in a certain area and time. Cabled and autonomous multidisciplinary deep-sea observatories can monitor the environment over longer timescales but with limited spatial coverage (Aguzzi et al., 2019, see Box 1). Spatial coverage can be increased by organising these stationary platforms into networks, complemented with mobile platforms, such as Remotely Operated Vehicles (ROVs) and benthic crawlers, as well as Human Operated Vehicle (HOV) operations (Purser et al., 2013, see Box 1). Furthermore, the biological complexity and abiotic properties (e.g. light, pressure, temperature) of the deep sea complicate the generation of reliable and representative data. Large surveying and sampling effort and thus extended ship time, as well as autonomous systems (e.g. deep-Argo, deep-AUV, deep-gliders) or mooring lines are required because the deep sea exhibits high spatial and temporal variability (see Section 4.5). In addition, the population densities of deep-sea species are generally very low, and sufficient replication is required to identify statistically significant ecological patterns and to evaluate disturbances.



A wave breaks on the working deck of the deep-sea capable research vessel FS *Polarstern*.



Credit: Bart De Smet and Francesca Pasotti, Ghent University

Amphipoda stet. sampled from the eastern Clarion-Clipperton Zone (Pacific Ocean) sediments at a depth of 4500 m as observed by a taxonomist using a microscope.

The significant difference in pressure (up to 100 MPa) and temperature (up to 30°C) between the Ocean surface and the deep sea causes substantial changes in the physiology and activity of organisms when samples are brought to the surface. This can lead to their death, changes in the physical and chemical properties of liquid samples, and alter microbial activity in these samples once they are on board (Tamburini et al., 2013). As a way to overcome some of the challenges on board, rapid storage or processing of samples in temperature-controlled rooms is required (Glover et al., 2016), which increases the costs and logistical complexity of a campaign. Alternatively, isobaric samplers can be used, which can maintain pressure and high temperature (Chavagnac et al., 2023), only pressure (for macro-organisms e.g. Shillito et al., 2023), or can fix the sample *in situ* (Mat et al., 2020). The extremely high temperatures of hot hydrothermal vents (i.e. up to > 400°C) represent another challenge for the materials used for sampling and *in situ* monitoring (Koschinsky et al., 2008).

Other challenges in deep-sea research are related to the time or timing needed for sampling or surveillance. Certain deep-sea phenomena occur sporadically and are unpredictable or difficult to predict (e.g. mesoscale eddies, upwelling/downwelling, convection/cascading, phytoplankton-bloom falls, whale-falls, jelly-falls), making them hard to study. Moreover, the deep sea generally features slow biological rates (e.g. slow growth rates) and ecological processes (McClain & Schlacher, 2015), demanding extended observation times (for instance for ecosystem recovery rates, see Marticorena et al., 2021 and Section 5.4).

Long-term studies and monitoring of the deep sea are essential to address the gaps (especially temporal) in our understanding. Two key locations to establish long-term monitoring are sentinel sites and protected areas. Sentinel sites are strategically chosen locations that serve as early warning systems for environmental and biological changes, providing continuous and detailed monitoring to detect and assess shifts in ecosystem conditions (Danovaro et al., 2020). Long-term monitoring and recovery studies in protected areas of the deep sea are also crucial to understand efficacy and recovery rates. Networks like the Long-Term Ecological Research (LTER)[30] or the European Multidisciplinary Seafloor and water column Observatory (EMSO)[31] play a key role, but lack sufficient coverage in deep-sea areas. Given the significant variability among deep-sea habitats, ranging from sediments and rocky outcrops to polymetallic crusts, nodules, and hydrothermal vents, as well as water column habitats, the selection of sites and establishment of different LTER networks tailored to various ecosystems and habitat types remains a logistical challenge.

Another significant challenge in deep-sea research is the limited availability of qualified scientists, including biologists (and especially taxonomists), geologists, and geophysicists, despite the growing demand (Engel et al., 2021). While emerging technologies like Artificial Intelligence, Virtual Reality, and the creation of Digital Twins of the Ocean are becoming increasingly popular, the expertise of traditional disciplines remains indispensable. These advanced technologies rely heavily on the high-quality scientific observations, data and insights generated by skilled researchers (Malde et al., 2020).

[30] https://lternet.edu/
[31] https://emso.eu/

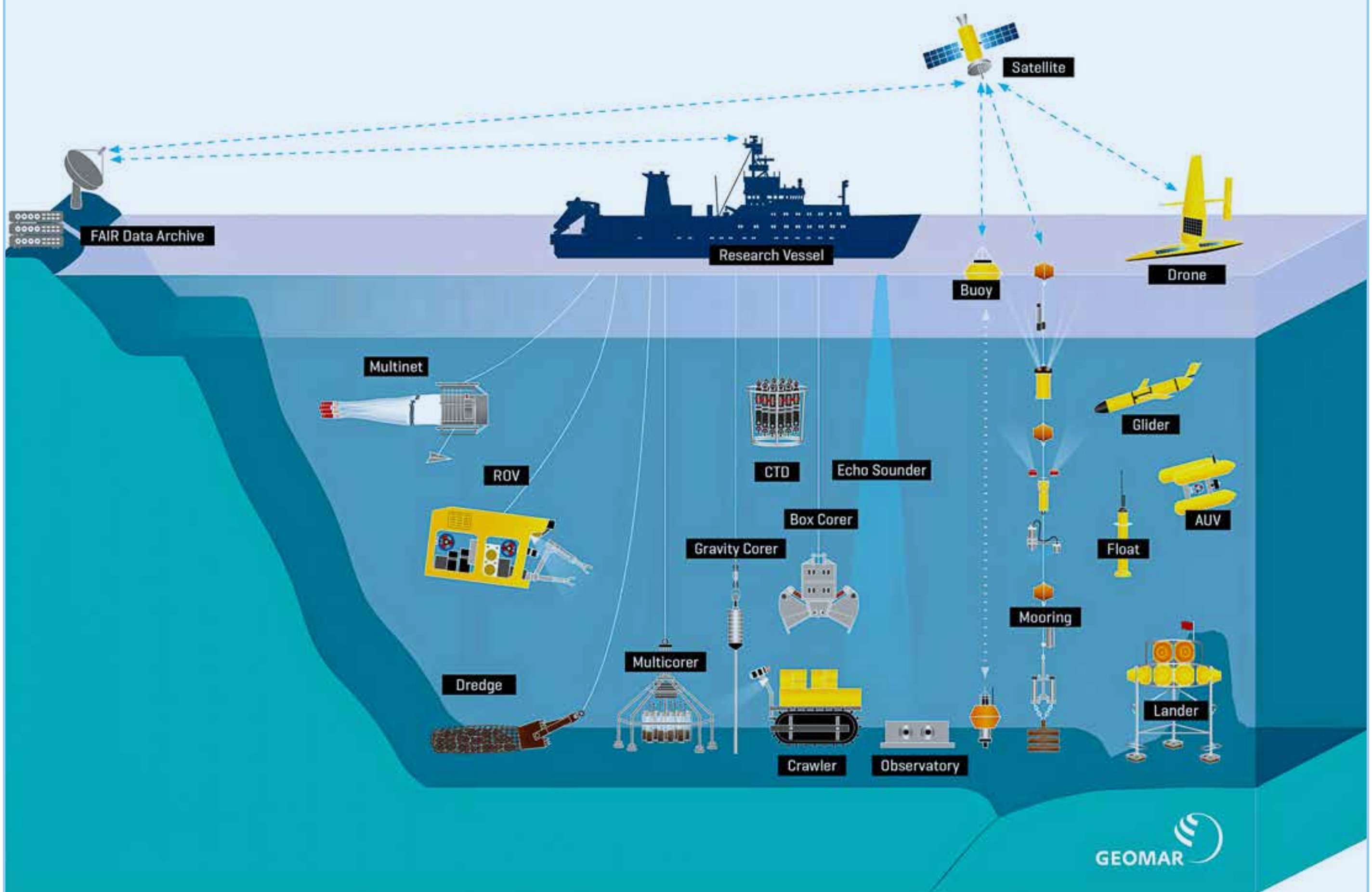
Despite the critical need for such expertise, the number of permanent positions in deep-sea science is currently very low and unevenly distributed globally. Although precise and overarching figures are not readily available, by February 2025, 1472 scientists from 271 institutions have provided biodiversity occurrences on the deep sea to the Ocean Biodiversity Information System (OBIS)[32]. Efforts to bolster the number of qualified researchers in this field are essential to meet the increasing challenges and opportunities presented by deep-sea exploration and conservation. The 2022 Global Deep-Sea Capacity Assessment provides a baseline of the technical and human capacity, and the unique regional challenges and opportunities for deep-sea exploration and research worldwide (Bell et al., 2022).

Shortcomings in data and sample management further impede the study of long-term and large-scale patterns and trends in the deep sea (Stocks et al., 2016). Historical samples and data (i.e. unarchived, non-digital legacy data) are often inaccessible or come with incomplete, or missing, essential metadata, rendering them non-compliant with the FAIR principles[33]. This affects our ability to understand temporal and spatial patterns and trends in areas and times without deep-sea observatories. Effective data and sample management is critical due to the growing complexity and size of datasets. This has been recognised internationally through the Barcelona Statement[34] from the 2024 Ocean Decade Conference and the Lisbon Declaration[35] of the 2022 UN Ocean Conference.

Because of the above challenges, only a fraction of the deep sea has been studied so far (see Figure 3.1). In addition, given the technical and infrastructural resources required to carry out deep-sea research, it is mainly conducted by scientists from developed countries in areas of their interest. This results in geographically biased knowledge of the deep sea (Howell et al., 2020). Furthermore, the current lack of long-term, globally comprehensive observations from the deep sea lead to limited and biased scientific data, creating high uncertainty and complicating evidence-based decision-making.

Finally, the impacts of research in the deep sea should be further studied, to be considered in pathways towards decarbonisation of research operations and for Environmental Impact Assessments.

Box 1: Tools for improving our understanding of the deep sea



Examples of current technology used to sample and monitor the deep sea from research vessels, and remotely. Figure not to scale

Credit: GEOMAR

[32] https://obis.org/
[33] Findable, Accessible, Interoperable and Reusable https://www.go-fair.org/fair-principles/
[34] https://Oceandecade.org/news/barcelona-statement-identifies-the-priority-areas-of-action-for-the-Ocean-decade-in-coming-years/
[35] https://www.un.org/en/conferences/Ocean2022/political-declaration

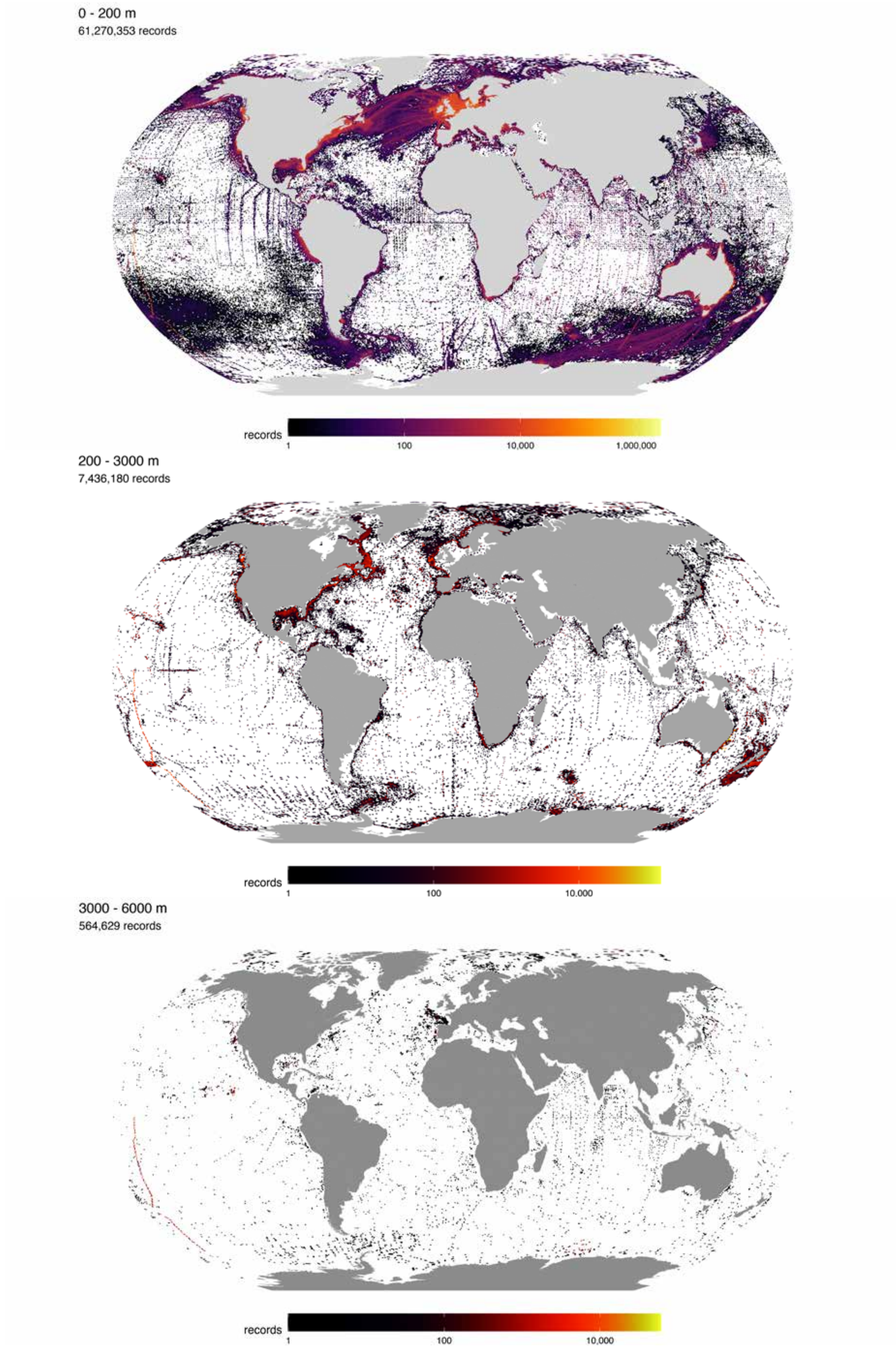
The deep sea is vast and deep, necessitating the use and continuous development of sophisticated technologies to explore it effectively, as highlighted in the EMB Position Paper Delving Deeper: Critical challenges for 21st century deep-sea research (Rogers et al., 2015). As electromagnetic waves do not penetrate water well, communication relies heavily on the use of acoustic waves. Furthermore, all technologies used in the deep sea must be able to operate under extreme conditions, including darkness, low temperatures and very high pressure.

Autonomous and cabled seafloor observatories are used to acquire continuous environmental data in the deep sea (Matabos et al., 2022). They receive power and communicate through batteries and cables, enabling remote, real-time and long-term monitoring of the deep sea. These observatories can be equipped with camera systems, and with multi-parametric biogeochemical, oceanographic, geophysical and biological sensors. These systems can, for example, identify, track, and count fauna (generally > 1 cm) clearly visible in seabed imagery using optoacoustic technology, combining the advantages of acoustics, optics, new molecular sensors (Aguzzi et al., 2015) and by using Artificial Intelligence (AI) and Machine Learning to generate data and/or pre-process data. However, autonomous deep-sea observatories can also provide long-term time-series of multi-disciplinary data (e.g. geological, physical, chemical, biological) at high temporal resolution for time periods of years to decades. Repeated submersible visits to study sites, combined with observatory maintenance, have documented submarine volcanic eruptions and associated changes to hydrothermal vent fields, changes in community structure and activity as well as interactions with other nearby chemosynthetic and surrounding ecosystems (Matabos et al., 2022 and references therein).

Despite their capabilities, fixed systems do not provide sufficient spatial coverage, so typically, a network of seabed observatories is required (Danovaro et al., 2017a), and/or mobile surveying instruments connected to the observatories to enhance spatial monitoring capabilities. Benthic surveying instruments include for example crawlers: Internet Operated Vehicles (IOVs) tethered to cabled observatories (Purser et al., 2013). These vehicles can be controlled and collect data in real-time via simple web browser interfaces controlled from anywhere in the world. Conversely, non-tethered benthic mobile crawlers (or rovers) are capable of automatically returning to a docking station for charging, data transfer, or recovery (Flögel, 2015).

To complement the seafloor monitoring capacities and extend monitoring into the water column, technological advancements provide opportunities to gather environmental data throughout the water column or at the water-sediment interface over longer periods. These new technologies include autonomous mooring lines, tethered ROVs, manned submersibles (e.g. the French Oceanographic Fleet's Nautile) and Autonomous Underwater Vehicles (AUVs, including gliders). AUVs and gliders may also dock to cabled observatories for energy recharge and data transmission (Bellingham, 2016). Underwater vehicles enable monitoring of the water column over extended periods and across various depths (Ludvigsen & Sørensen, 2016). AUVs equipped with imaging or acoustic devices are particularly suited for mapping habitat and biota distribution (Morris et al., 2014). Although ROVs are tethered, they also offer high mobility similar to AUVs (Robison et al., 2017) and have the advantage of two-way real-time data transmission. They can use manipulator arms and other tools to collect discrete high-quality samples, conduct experimental work, or to maintain observatories.

Dedicated multidisciplinary oceanographic cruises provide snapshots of the deep-sea location(s) under investigation. Traditional instruments like rosette-CTDs, box-corers, multi-corers, gravity-corers, dredges, and multi-nets are needed to collect samples and obtain detailed information, identify new species, perform process studies, and conduct specific analyses not covered by available sensors, and are crucial to improve our understanding of the deep sea. Multibeam echosounders and Moving Vessel Profilers (MVP) can provide critical physical data of the water column and seafloor while the ship is underway. The resulting data collected can be integrated with the broader monitoring efforts of deep-sea observatories, crawlers, ROVs, AUVs, and gliders. Sophisticated models, and potentially AI fed by multidisciplinary data collected at multiple spatial and temporal scales, can help to understand how deep-sea biodiversity and ecosystem functions change with increasing anthropogenic impacts which already reach the deepest parts of our Ocean.



Credit: Pieter Provoost, OBIS; https://github.com/iobis/sampling-effort-depth

Figure 3.1 Sampling effort by depth layer based on Ocean Biodiversity Information System (OBIS) biodiversity occurrences in 2024. Dots displayed on the map represent current pelagic and benthic biodiversity records in OBIS. The deep sea is largely unexplored due to technical, practical and financial challenges, leading to geographically and bathymetrically biased scientific data. OBIS contains seven times more records for shallow waters (0 - 200 m) compared to deep waters (> 200 m), and less than 1% of all Ocean biodiversity records are from abyssal depths (> 3,000 m).

4 Knowledge gaps in understanding the deep sea and Ocean health

4.1 Biological deep-sea science gaps

To assess the impacts of human activities on deep-sea ecosystems, baseline assessments are needed of biodiversity and ecosystem functions and services, both on the seafloor and in the water column. Below we elaborate on the primary knowledge gaps for different deep-sea biological research domains.

4.1.1 Biodiversity science gaps

Species-level biodiversity information is key to understanding ecosystems, and to track and predict environmental impacts (Rabone et al., 2023). It is estimated that about two million eukaryotic species (i.e. animals, plants, and fungi) may live in our Ocean (Bouchet et al., 2023). According to the World Register of Marine Species (WoRMS)[36] only 246,000 marine species have been described to date, of which only about 30,000 are deep-sea organisms (see World Register of Deep-Sea Species (WorDSS)[37] and Glover et al., 2024). Clearly, the deep sea harbours many undiscovered organisms, especially smaller organisms and microbial life. For example, in the Clarion-Clipperton Zone, a relatively well-investigated deep-sea region that is being explored for polymetallic nodule extraction, only about 8% of collected benthic animal species have been described (Figure 4.1; Rabone et al., 2023). In addition, deep-sea microbial diversity (i.e. bacteria and archaea) is expected to be extremely high. In the water masses of the North Atlantic for example, besides several species that dominate the samples, thousands of low-abundance microbial species populations account for an extremely rich and ancient phylogenetic diversity, representing a source of genomic innovation (Sogin et al., 2006).

The symbiotic relationship between chemosynthetic bacteria and eukaryotic hosts that was discovered at deep-sea hydrothermal vents can be now found almost everywhere in the Ocean (Sogin et al., 2020). These symbioses evolved independently multiple times, and are shown by rich diversity in chemosymbiotic body plans and functional diversity that can power entire ecosystems. The full biodiversity of these chemosymbiotic associations is unknown (Sogin et al., 2020). These symbioses, representing rich biodiversity and functional diversity, directly influence ecosystem-level flows by powering entire ecosystems and driving biogeochemical cycles. Research is needed to uncover the biochemical, physiological and molecular mechanisms that govern interactions between the symbiotic partners, and to understand their role in ecosystem functioning.

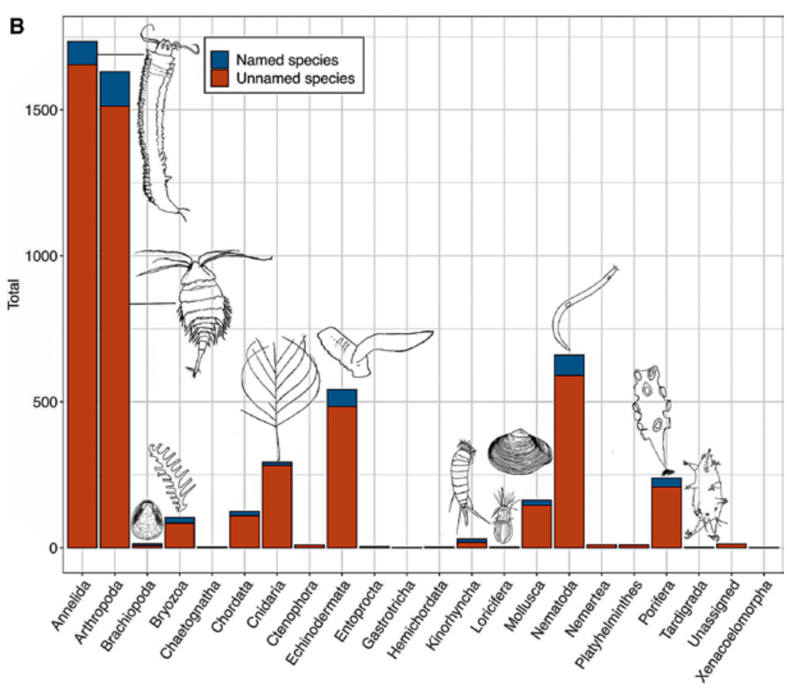


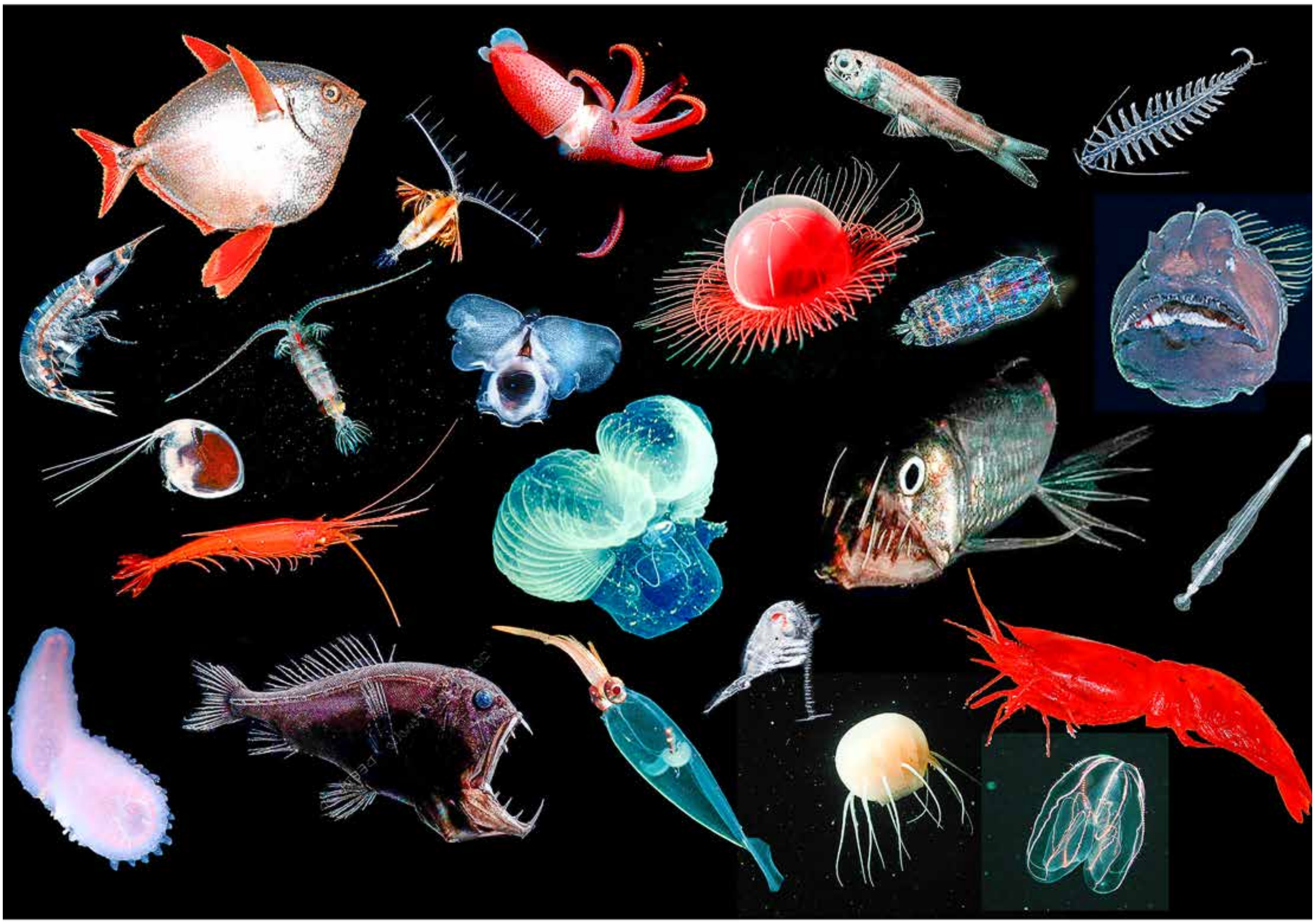
Figure 4.1 The proportion of unnamed versus named animal species per phylum in the sediments of the Clarion-Clipperton Zone (CCZ), in the northeastern Pacific Ocean. Named species are shown in blue, and unnamed species in red. Drawings of some of the newly described CCZ species are shown per phylum for illustration purposes. "Unassigned" includes those species not assigned to phylum level.

[36] https://www.marinespecies.org/aphia.php?p=stats
[37] https://www.marinespecies.org/deepsea/

The Ocean Biodiversity Information System (OBIS, see Figure 3.1) and the Global Biodiversity Information Facility (GBIF) for animal groups (Hughes et al., 2021) show that less than 0.6% of the global Ocean seafloor area has been sampled for biodiversity studies. A recent survey of global Ocean metagenomes underscores the under-sampling of the deep seafloor, with only 4% of the 2,102 Ocean metagenome samples available in the European Nucleotide Archive[38] being benthic. Most samples (78.5%) were collected in the upper Ocean (depth 0 - 200 m), which represents only 5.2% of the Ocean volume; 7.2% samples were collected from the mesopelagic Ocean (200 - 1,000 m) and 10.2% from the dark Ocean (> 1,000 m), the largest Ocean biome by volume (Laiolo et al., 2024). The largest gaps in biodiversity baselines are found in areas where deep-sea research and exploration capacities face the biggest challenges (see Figure 3.1).

Deep-sea biodiversity and ecosystem functioning studies have revealed that the functioning of deep-sea ecosystems is typically positively related to higher levels of biodiversity (Danovaro et al., 2008), although with different patterns for different taxa and systems (Pape et al., 2013). These positive relationships suggest that more biodiverse deep-sea systems are characterised by higher rates of ecosystem processes and increased efficiency in performance. Functional biodiversity, including microbial and macrofaunal contributions to nutrient and carbon flows, enhances the ability of deep-sea benthic systems to carry out key biological and biogeochemical processes critical for their sustainable functioning (Thurber et al., 2014). Understanding the relationship between biodiversity, ecosystem functioning and services, and how they change with global change, is therefore crucial. A key priority for future research is experimental studies linking species diversity to specific ecosystem functions, which are crucial for developing predictive ecosystem models.

Baseline knowledge is critical for understanding and predicting how deep-sea ecosystems respond to human-induced stressors and for identifying how they might deviate from natural variability. This understanding becomes even more important in the face of global changes, where multiple stressors are likely to significantly influence future trends. For example, climate change is expected to increase the biomass of several commercially valuable Pacific tuna species in the Clarion-Clipperton Zone, a prime target for future deep-seabed mining, which will create complex interactions between different users of this area and environmental stress (Amon et al., 2023). While shifts in species distribution due to Ocean warming are certain, there is limited knowledge about specific impacts. However, negative effects on many mesopelagic and deep-sea fish stocks are likely to occur (Martin et al., 2020).



Midwater animal biodiversity: Squid, fish, shrimp, copepods, medusa, filter-feeding jellies, and marine worms are among the midwater creatures that could be affected by deep sea mining. Photos by E. Goetze, K. Peijnenburg, D. Perrine, Hawaii Seafood Council (B. Takenaka, J. Kaneko), S. Haddock, J. Drazen, B. Robison, DEEPEND (Danté Fenolio), and MBARI.

[38] https://www.ebi.ac.uk/ena/browser/

The robustness and resilience of deep-sea ecosystems to a warming, less oxygenated and more acidic Ocean, and consequences for ecosystem functions and services are poorly understood, although this information is urgently needed to manage Ocean exploitation, protection, restoration, and improve Ocean health. Linking results from *in situ* observations to *in-* and *ex situ* experiments will be crucial to understand and predict how deep-sea ecosystems will change with global change. Further investigations are needed to understand how deep-sea ecosystems will change in light of increasing anthropogenic activities.

High-pressure experiments can simulate deep-sea conditions for species and ecosystems, providing insights into how stressors affect biodiversity and functioning. Long-term, high-pressure laboratory studies are needed on species robustness and resilience to address changes under specific temperature conditions. This will create a "response baseline" to address how biodiversity, ecosystem functions and services, may be impacted by anthropogenic pressures. Studies are also needed on the responses of species to stressors like pollutants, as, for example, some deep-sea bacteria can degrade plastic and remove contaminants (Gui et al., 2023), offering possibilities to address plastic pollution. Furthermore, the ability of deep-sea organisms to adapt to high pressures may be used for bio-inspired studies and ultimately human applications.

To start filling the gaps between taxonomic and functional biodiversity, untargeted (non-marker) metagenomic and metatranscriptomic studies are needed to better understand the functional properties and drivers of deep-sea biological communities and their relationship with their physical, chemical and biological environment. Moreover, multi-domain studies (e.g. from bacterial to metazoan species) are needed to avoid missing ecological links that can be crucial for ecosystem health.

4.1.2 Biological carbon pump knowledge gaps

The oceanic Biological Carbon Pump (BCP, Figure 4.2) is a crucial process whereby, over long time-scales, a substantial fraction of atmospheric CO_2 is removed and stored (European Marine Board, 2023). This process involves fixing CO_2 through photosynthesis in the sunlit (euphotic) epipelagic zone of the Ocean, from where it is transported into the dark deep sea, via the meso- and bathypelagic to the deep seafloor (Eppley & Peterson, 1979). This makes deep-sea sediments the largest carbon storage system on Earth. However, climate change is impacting this natural function through increased water stratification, changes in upwelling and ice cover, acidification, deoxygenation, and warming (Ibarbalz et al., 2019) thereby potentially changing the contribution of the deep seafloor to carbon storage (Siegel et al., 2023).

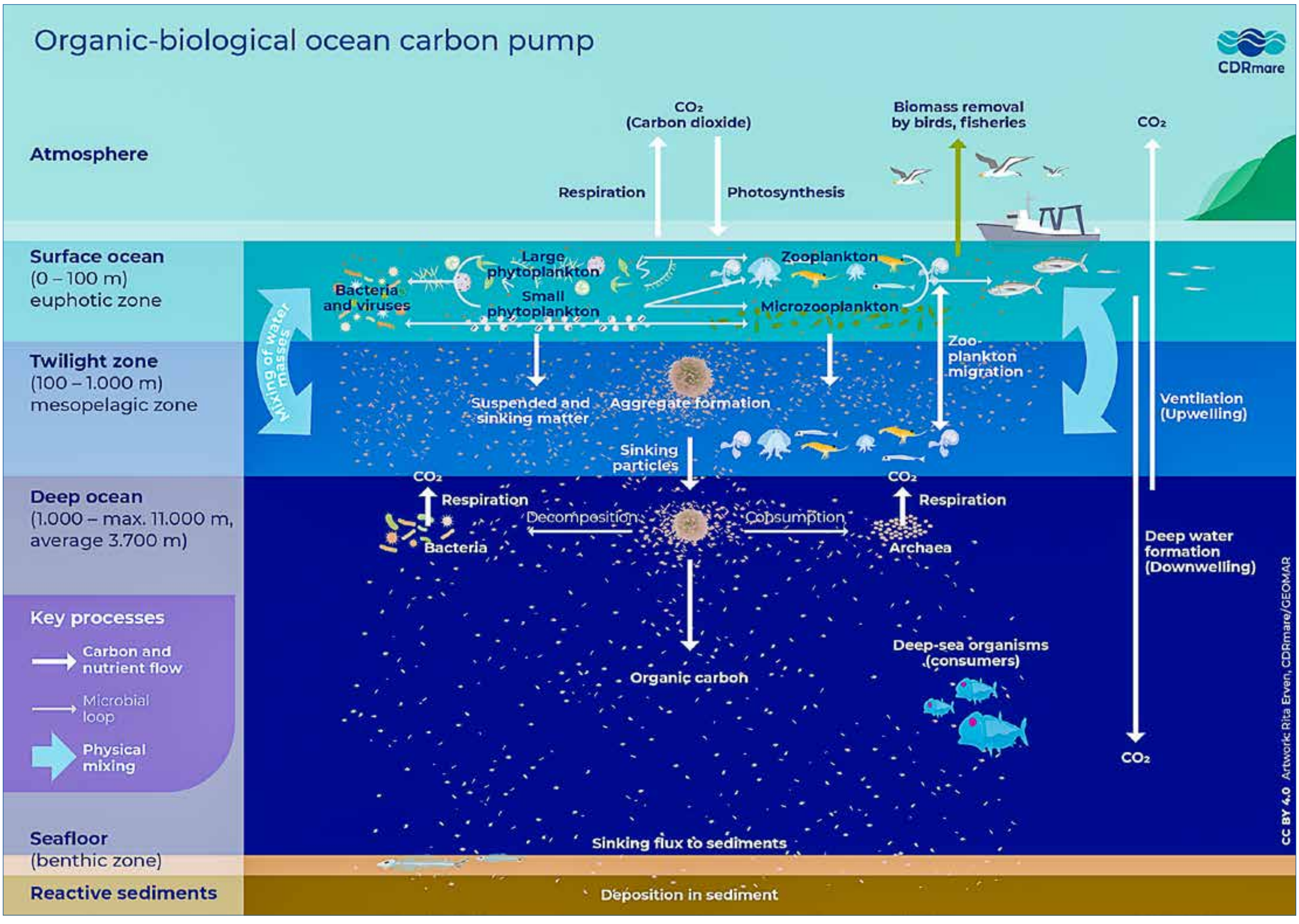


Figure 4.2 Illustration of the organic-biological Ocean carbon pump, an important process that removes the greenhouse gas carbon dioxide from the atmosphere and stores it in the sediments in the deep sea, thereby contributing to climate regulation. Note that the definition of deep sea presented here differs from the one considered for this document.

The BCP consists of many processes (Boyd et al., 2019), each involving different species or communities. Currently, we lack the integrative view necessary to understand its baseline functioning and to model and predict its future performance. Predicting the strength and efficiency of the BCP remains challenging, especially since remineralisation (the biogenic transformation of organic matter into dissolved inorganic carbon, or decomposition, consumption and respiration in Figure 4.2) and sinking are poorly understood below the euphotic zone. Utilising the BCP as a blue carbon pathway to mitigate elevated greenhouse gas concentrations is hindered by this lack of knowledge about its functioning and the impacts of human activities (Howard et al., 2023).

Within the mesopelagic zone (200 – 1,000 m, see Figure 1.2), gravitational-sinking particles are transported, processed, and transformed (Boyd et al., 2019). Half of the organic matter degradation occurs via particle transformation (Briggs et al., 2020) particularly through microorganism-driven remineralisation (Simon et al., 2002). However, in the mesopelagic waters, the imbalance between carbon demand by consumers of the primary producers (heterotrophs) and its supply, predominantly by sinking carbon through the BCP remains poorly constrained (Baumas et al., 2023). This is partly due to methodological issues (Burd et al., 2010), and a lack of understanding of microbial processes such as the need to consider the chemoautotrophic processes in deep oxygenated waters (Herndl et al., 2023). Experimental studies linking microbial and zooplankton contributions to carbon flux with physical parameters (e.g. particle sinking rates) are needed to integrate functional biodiversity into carbon flow models. Linking biodiversity and biogeochemical processes will improve predictions of the BCP's efficiency and its response to anthropogenic pressures. Finally, the deep carbon pump is also fuelled by the poorly understood microbial activity from hydrothermal plumes (Cathalot et al., 2021), and bioturbation, i.e. the reworking of particles and sediments by organisms (Míguez Salas et al., 2024).

Zooplankton also play a significant role in the BCP (Hernández-León et al., 2020). Mesozooplankton migration is estimated to contribute 0.9 – 3.6 PtC y-1 (pentagrams of carbon a year) to the carbon exports with a carbon sequestration timescale of 250 years (Pinti et al., 2023). Mesopelagic fish support enormous biomass in the midwater, but their vertical migrations (Figure 4.3) and their role in carbon transport are largely unquantified (Martin et al., 2020). The exploitation and degradation of the mesopelagic layer threaten fish stocks and could have a detrimental impact on the BCP, which could ultimately exacerbate climate change, highlighting the urgent need for scientific efforts to better understand the BCP (Martin et al., 2020). The role of species living between the euphotic zone and the seafloor in the processing of organic matter remains largely unquantified. Research is needed to understand the impact of vertical migration on the efficiency of the BCP (Martin et al., 2020).

Another missing link in the BCP is the function and magnitude of carbon circulated in the "jellyweb", a midwater food web consisting of detritivorous and carnivorous gelatinous fauna (Robison, 2004). These species are fragile and difficult to sample, but *in situ* observations using submersibles and camera systems are helping to identify their role. Specific gelatinous species, such as zooplankton (Christiansen et al., 2018), jellyfish (Sweetman et al., 2014) and pelagic tunicates (Stenvers et al., 2021) may have a significant local impact on the BCP, but their overall role for the majority of mesopelagic fauna remains unknown.

Carcasses of large pelagic animals (e.g. whales), as well as large continental vegetal inputs (e.g. tree trunks) are also relevant to the BCP, since they sink quickly (Drazen et al., 2008), becoming food for benthic scavengers and bone and wood borers. Whale carcasses host unique communities for years (Li et al., 2022). Smaller carcasses of squid, fish and jellyfish are consumed within days (Smith et al., 2015). The flux of nekton and zooplankton carcasses may have a significant contribution at a local scale to the BCP (Halfter et al., 2022) but data are extremely scarce due to the difficulty in distinguishing between zooplankton swimmers and "true" carcasses of zooplankton in sediment traps (e.g. Yang et al., 2022).

Most deep-sea environments depend on primary production in the sunlit euphotic zone (i.e. photosynthesis) and the resulting flux of organic matter via the BCP. However, chemosynthesis (*in situ* primary production using energy from inorganic chemicals rather than sunlight) occurs at deep-sea hydrothermal vents, hydrocarbon seep systems, whale falls, and deep hypersaline anoxic basins (Sogin et al., 2020). Dark CO_2 fixation (the production of prokaryotic biomass from CO_2 fixation by chemoautotrophs) in the water column can be as substantial as heterotrophy (Reinthaler et al., 2010) and represents new biomass production that is often overlooked. The significance of dark carbon fixation for oceanic primary production needs future investigation (Herndl et al., 2023). Recent discoveries have also shown that minerals at inactive hydrothermal vents host microbial communities that are important for deep-sea primary productivity (Achberger et al., 2024).

Lastly, the role of viruses in marine ecosystems is acknowledged but poorly understood. Viruses are the most abundant biological entities in the Ocean, with the highest number of organisms per litre of seawater and have major biogeochemical implications through the mortality of their microbial hosts and the metabolic reprogramming caused during the viral infection. However, current knowledge remains largely theoretical. The extent and dynamics of viral infections and the fate of infected microorganisms remain poorly quantified, particularly in deep marine ecosystems (He et al., 2024). A better understanding of these processes is essential to grasp the role of the viral component in the BCP through the water column.

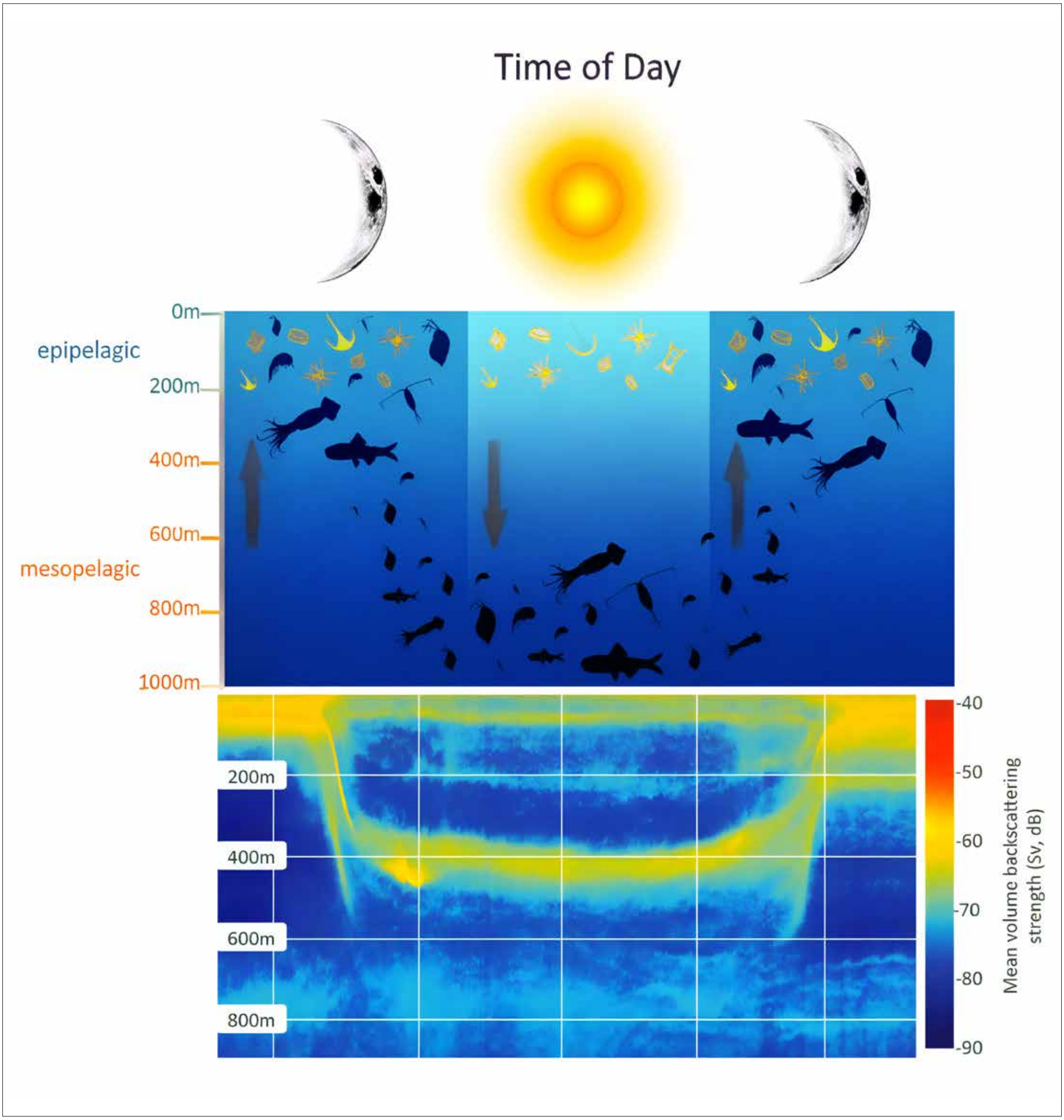


Figure 4.3 Illustration of diel vertical migration, the largest migration on the planet, carried out by animals in the water column of our Ocean. When light reaches a minimum threshold, zooplankton and small fishes ascend from several hundred metres below the surface, forming dense, detectable layers of organisms (bottom figure, echogram), to feed in the highly productive surface waters, protected from visual predation. At daybreak, they migrate back to the safety of the deeper (depths of hundreds of metres), mesopelagic waters where darkness protects them from predators. The echogram (bottom figure) illustrates the ascending and descending phases of the diel vertical migration through the water column. The yellows and reds indicate the highest densities of animals

4.2 Biogeochemical deep-sea science gaps

Our understanding of the biogeochemical cycles of elements in the Ocean, including the deep sea have been significantly enhanced by GEOTRACES[39]. It showed that hydrothermal vents are a crucial, not previously accounted, source of certain dissolved trace metals, such as the important micronutrient iron (e.g. Fitzsimmons et al., 2014). New hydrothermal vent fields are discovered annually, yet the extent of hydrothermal heat, fluid fluxes, and the resulting element fluxes (e.g. trace metals like iron) generated by the circulation of Ocean water through the Earth's crust remains unknown (Chavagnac et al., 2018). Specifically, information on the spatial and temporal dynamics of hydrothermal plumes is lacking. Recent studies have shown that hydrothermal plumes in the deep sea are significant sources of particulate organic carbon (POC), enhancing microbial heterotrophic production rates within the plumes similar to the POC export fluxes reported for the deep sea (Cathalot et al., 2021). Additionally, it is important to determine whether these plumes from the deep sea provide trace metals and other nutrients to the euphotic zone, thereby supporting primary productivity. This has been demonstrated in the Western Tropical South Pacific, where high dissolved iron concentrations from a submarine source impact the surface productive layer (Guieu et al., 2018). How and if hydrothermal iron is transported from the deep sea to the photic zone by physical mechanisms, such as tidal, contour, and local or regional upwelling currents, is unknown. Likewise, while there is some understanding of the geochemical reactions responsible for the composition of hydrothermal fluids in certain vent fields, a deep understanding and ability to forecast mineral transfer from the crust to the hydrothermal fluid and into the deep sea remain elusive.

Credit: ROV-Team/GEOMAR

Over the course of millions of years, an ecosystem has developed around black smokers that is perfectly adapted to conditions that are commonly hostile to life.

39 https://www.geotraces.org

Advancing knowledge on biogeochemical conditions and processes in the deep sea may offer clues about how life started on Earth and inform on potential conditions in space that can support life (e.g. exoplanets). Despite their relevance to questions about the origin of life, very few alkaline hydrothermal vents such as “Lost City” - that fulfil the, believed to be, abiotic conditions common on Earth before there was life - have been found to date (Aquino et al., 2022). In addition, the recent discovery that polymetallic nodules on the seafloor of the Pacific Ocean's Clarion-Clipperton Zone could be producing “dark oxygen” (Sweetman et al., 2024) suggests a potential existence of an additional abiotic oxygen source, although the extent and importance of this finding has to be clarified. Future studies on dark oxygen production may also shed new light on Earth's oxygenation and biological evolution.

The deep subsurface of the Ocean also requires attention to better understand Earth's formation and evolution and the connections between tectonics, climate, the planet's habitability and biodiversity. Current knowledge, gained through Ocean drilling, about the composition of the Earth's mantle, which constitutes 67% of its mass and 84% of its volume, remains limited. Although hydrothermal subseafloor microbial communities are common (McNichol et al., 2018), overall production rates and carbon flow are unknown. The role of deep microbial activity in the Earth's upper crust needs further research, as the microbial communities can change in abundance, diversity and function in response to geological activity or environmental pressures (Zhang et al., 2022). The recent discovery of animal life in subseafloor cavities in the Earth's crust below hydrothermal vents (Bright et al., 2024) raises questions about global biodiversity, the geological extent of this unseen habitat, and the interactions between metazoan life and biogeochemical and biological processes on the seafloor and in the water column.

4.3 Physical deep-sea science gaps

The understanding of spatial and temporal variability of the physics of the deep sea is fragmented and patchy due to limited observations. The upper layers of the deep sea are primarily driven by the wind and better observed with operational global systems such as Argo profiling floats (Riser et al., 2016). However, the mean depth of the Ocean is about 3,700 m, so the majority of the global Ocean volume is out of the reach of these systems. Below 2,000 m, the most common observational approaches are individual ship surveys and long-term moored observations. Changes in the deep sea below 2,000 m are often finer than the accuracy of the sensors used, and only multi-year time series can deliver robust trends. Coordination of observations within global initiatives that define common practices, such as the Global Ocean Observing System (GOOS) networks and programmes, ensure the data interoperability needed to detect long-term physical changes such as deep-sea warming and changes in salinity (Purkey et al., 2019).

The dynamics in the deep sea below 2,000 m are driven by large scale density differences and ventilation[40] of these layers in a few regions, where deep convection occurs (Marshall & Schott, 1999). In addition, the deep sea is prone to regional- and local-scale mixing between deep-water layers in complex processes that are studied in internationally coordinated experiments (Wynne-Cattanach et al., 2024). These deep-sea mixing processes influence nearly every aspect of Ocean dynamics (Meredith et al., 2022), from the variability of major Ocean currents and water mass transport (Sasaki et al., 2018) to changes in the deep-sea heat content (Spingys et al., 2021) and key climatic patterns, such as monsoon oscillations, changes in the El Niño–Southern Oscillation (ENSO, Warner & Moum, 2019) and the strength of the Meridional Overturning Circulation (MOC, Cimoli et al., 2023). The MOC is vital for transporting heat, carbon, oxygen, and nutrients across the globe and with depth. Although recent studies show that the Southern Ocean plays a key role in the MOC (see Figure 4.4 and Lee et al., 2023), deep-sea observations and data from this area are generally lacking (Bennetts et al., 2024), and therefore climate and Ocean models fail to predict the mean state or long-term trends of the MOC. In addition, the collection of deep-sea current baseline data of the Atlantic Meridional Overturning Circulation (AMOC) is essential to predict its behaviour and understand how it has been impacted by climate change, as the risk of its collapse before 2100 is higher than has previously been estimated (van Westen et al., 2024).

The deep sea absorbs significant amounts of heat and carbon dioxide, acting as a buffer against climate change (IPCC, 2019), but resulting in warming of deep waters. Deep-sea warming has several implications, including its contribution to sea level rise (Kouketsu et al., 2011), changes in stratification and impact on nutrient cycling, which in turn affect GHG uptake by the deep sea and/or contribute to biodiversity loss. Global warming reduces the total kinetic energy of the Ocean, even if surface currents accelerate due to warming, as increased vertical stratification limits energy transfer in the deep sea. As a result, the deep sea becomes calmer, impacting heat and carbon absorption. This is particularly due to weakened mesoscale eddies (Wang et al., 2024), swirling oceanic circulations about 100 km in diameter, which can extend down to 1,000 m, and act as the “weather” of the Ocean (Purkiani et al., 2022).

Both mesoscale and submesoscale (200 km to tens of metres) physical dynamics influence biogeochemistry and ecosystem structure by transporting nutrients from the depths to the photic zone. Basin-scale circulation, which redistributes physical and biogeochemical properties, is also highly affected by mesoscale and submesoscale processes. The role of long-lived mesoscale eddies in the storage of carbon and heat, as well as in nutrient and contaminant distribution, is significant but still poorly understood. Moreover, deep-sea currents and eddies contribute to the global redistribution of temperature, salinity, and key elements such as oxygen and carbon. These factors, in turn, impact the MOC, oceanic heat absorption, climate, and marine ecosystems. Although mesoscale and eddy interactions remain vital, there are still significant knowledge gaps regarding the rate and extent of MOC changes.

[40] Ocean ventilation refers to the transport of surface waters into deeper layers.

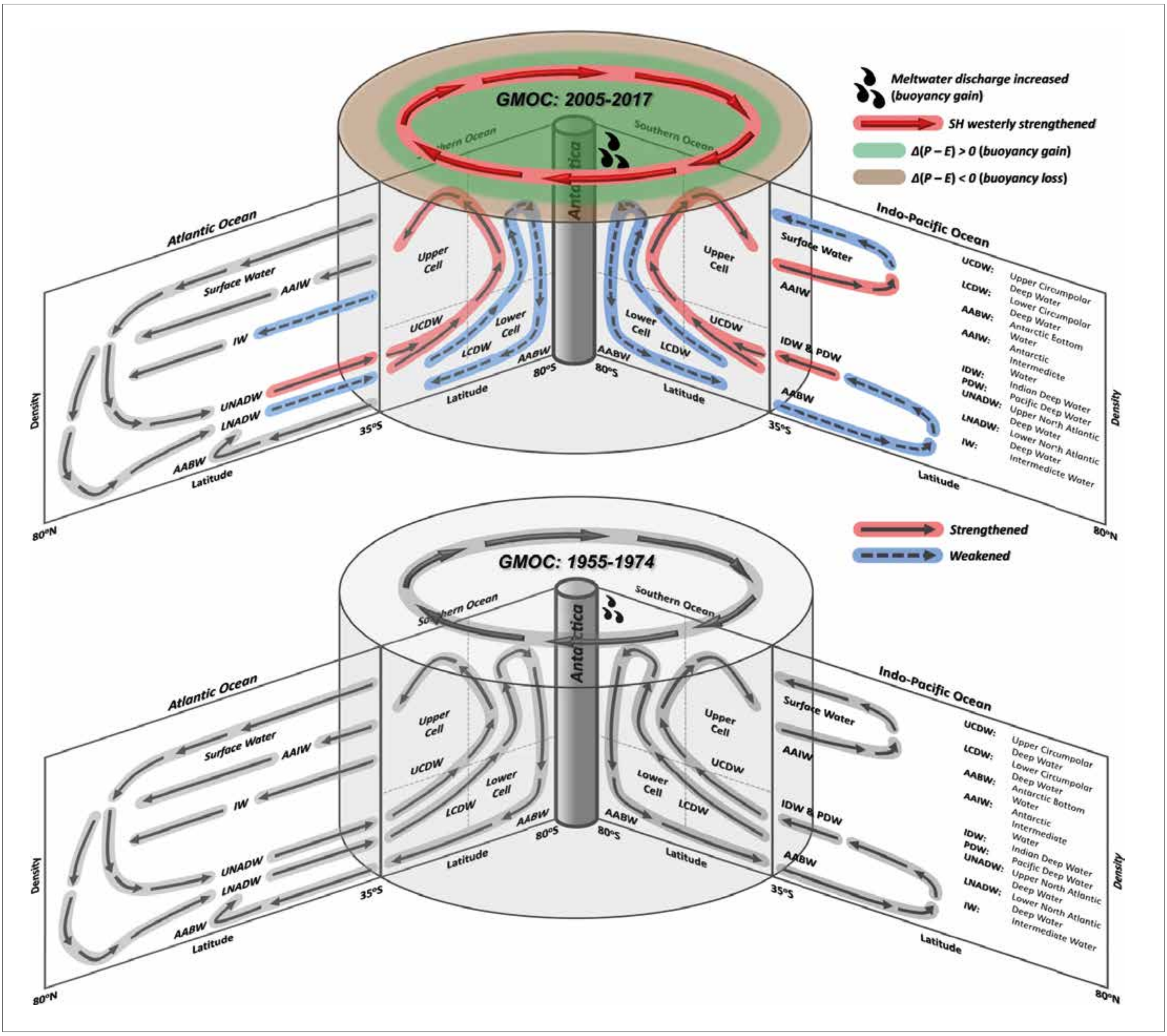


Figure 4.4 A summary schematic of the Global Meridional Overturning Circulation (GMOC) in (upper panel) 2005–2017 and (lower panel) 1955–1974. The major drivers of the changes in the GMOC, namely the increases in Southern Hemisphere (SH) westerly winds and Antarctic meltwater discharge, and the reduced precipitation minus evaporation changes in 2005–2017 compared to 1955–1974, are also indicated in the upper panel.

Internal waves are another major source of turbulent mixing (from metres to millimetres), affecting all scales of Ocean circulation, from the abyssal plains to the surface and from the open Ocean to coastal regions. They can range in scale from hundreds of kilometres to tens of metres, but data especially from remote areas is still limited (Lévy et al., 2012). Microstructure sensors that measure turbulence are being integrated into autonomous vehicles, such as gliders, profiling floats, etc. (see also Box 1) and coupled with biogeochemical sensors to better parametrise fine-scale and oceanic turbulence and its influence on biogeochemical processes. This will improve the representation of Ocean circulation in models at finer spatial and temporal scales.

The Mixed Layer Depth (MLD), which can reach depths of up to 500 m, is where water properties become relatively homogeneous due to mixing, and is crucial for understanding deep convection and the vertical transport of water properties (Kantha & Clayson, 1994). The MLD plays a critical role in global thermohaline circulation by mediating the interaction between atmospheric and oceanic processes. Given the spatial and temporal variability of the deep sea, understanding how MLD varies across regions and timescales is key to comprehending deep convection and water mass transport, including remote areas of the Southern Ocean (Bennetts et al., 2024). To enhance our understanding of deep convection and mixing, continuous monitoring of thermohaline properties, along with chemical parameters like oxygen and pH, is required at finely tuned temporal intervals. This will provide more detailed insights into the complex dynamics of the deep sea and the impacts of environmental change.

Despite the evolution in our understanding of Ocean mixing, gaps remain, particularly in relation to the interaction between Ocean mixing and bathymetry at mesoscale levels (Polzin & McDougall, 2022). Large parts of the deep sea remain unexplored due to logistical difficulties (see Chapter 3), and without higher resolution bathymetry datasets (see Section 4.4) we cannot fully understand global Ocean mixing. Data collection in remote areas is crucial to fill the knowledge gaps in deep-sea temperature changes, currents, mixing, and eddies. Free-drifting oceanographic floats, such as Deep Argo floats are commonly used but only provide data down to 2,000 m depth and have limited temporal resolution (Zilberman et al., 2023).

Developing improved observational tools is critical. Integrating sensors into undersea telecommunications cables (SMART cables) may offer a cost-effective solution for global Ocean observing. These sensors could provide critical data on temperature, pressure and seismic activity, which would improve climate models (Howe et al., 2019).

Developing improved modelling techniques is also critical (Courtois et al., 2017). Integrating accurate deep-sea processes into climate models will improve predictive accuracy. Physical Ocean mixing models need to be combined with biodiversity-function studies to understand the role of mixing in nutrient redistribution and its impact on benthic and pelagic ecosystems. Interdisciplinary experiments that integrate physical, chemical, and biological parameters can enhance predictive models of nutrient cycling and ecosystem responses to climate change. Currently, uncertainties remain about the best ways to represent deep-sea dynamics and the vertical distribution of heat, nutrients, and other properties in climate simulations.

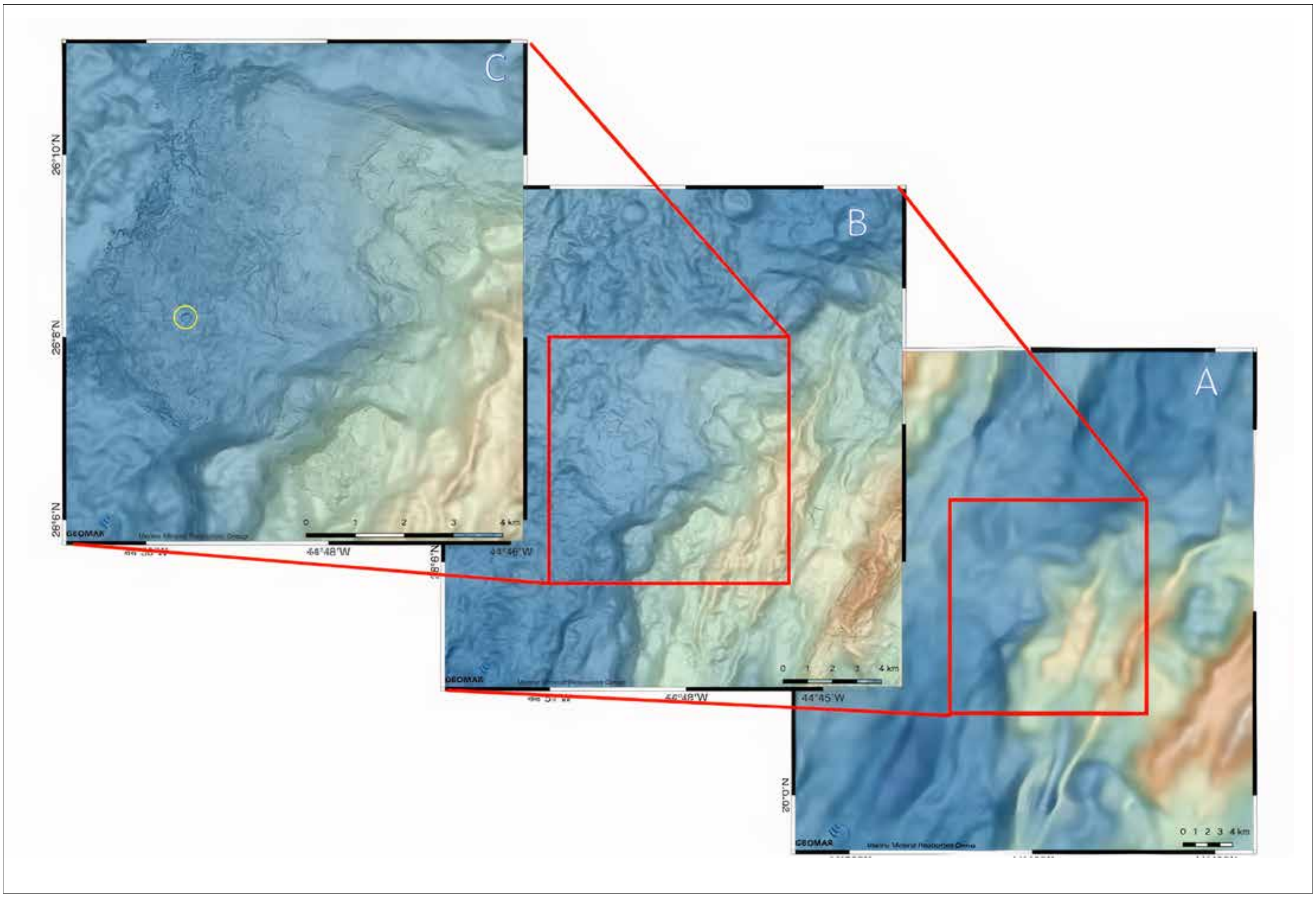
The key knowledge gaps in physical oceanography research relate to deep-sea heterogeneity of dynamical processes, water mass transformation, warming, the extent and rate of changes in the MOC, and the role of mesoscale and submesoscale eddies in carbon and heat storage. Limited data from remote and deep areas, particularly in the Southern Ocean, hampers accurate predictions of long-term trends. Furthermore, uncertainties persist regarding the interaction between Ocean mixing processes and bathymetry. Continuous monitoring and improved observational tools are needed to fill these gaps. Modern deep-sea observing aims for a holistic view of the deep sea and requires interdisciplinary research to be conducted.

4.4 Geological deep-sea science gaps

The detailed mapping of the seafloor (bathymetry) at sufficient spatial resolution is essential for understanding various geological processes and their products, such as bedforms resulting from bottom currents, submarine glacial landforms, benthic habitats, and geohazards like shallow faults, pockmarks, or mass transport complexes. For more information, see EMB Position Paper on Marine Geohazards (Kopp et al., 2021). The resolution required depends on the research objective, and high-resolution mapping that includes biological information is required for some applications (see EMB Future Science Brief on Marine Habitat Mapping, Fraschetti et al., 2024). High-frequency multibeam echosounders (> 400 kHz, see Figure 4.5) or optical techniques (e.g. photogrammetry/ video mosaics) mounted on AUVs or ROVs (Kwasnitschka et al., 2016), can achieve metre to centimetre-scale resolutions typical of shallow water surveys (Normandeau et al., 2022). However, such high resolutions are not standard. In 2024, only 26.1% of the global seafloor has been mapped with echo-sounders[41], with the rest estimated based on satellite-radar measurements with large uncertainties and low resolution of around 6 km (see Figure 4.5). Completing this mapping could take a single ship 200 years (Mayer et al., 2018). The NIPPON foundation - General Bathymetric Chart of the Oceans (GEBCO) initiative “Seabed 2030”[42] aims to map the entire seabed by 2030 for the benefit of science and people. The project aims to discover how much of the seafloor has been mapped already and what might be held in the world's repositories. All existing bathymetric data will be compiled and shared in the freely available GEBCO digital map, which will then identify areas where there is no data to inform future mapping expeditions.

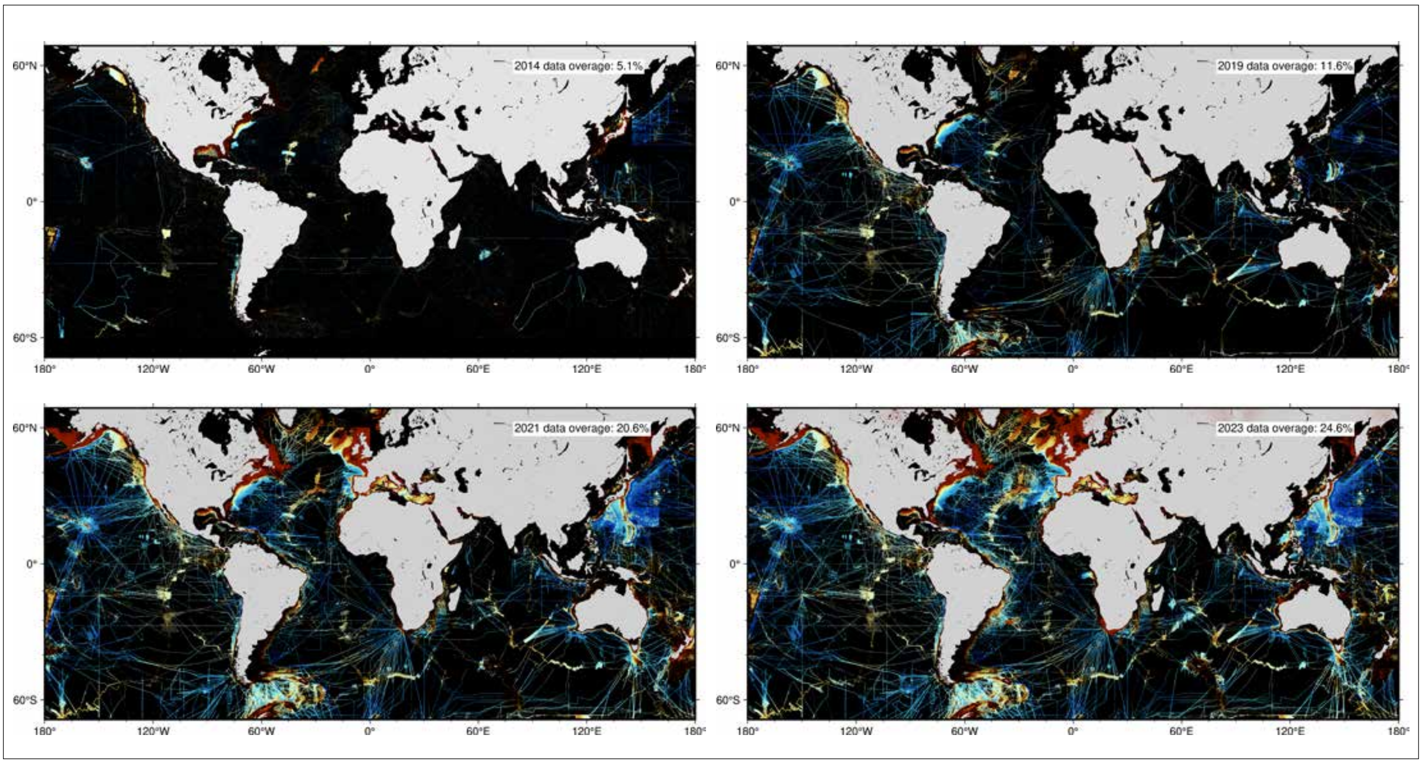
Global bathymetric datasets, such as those from GEBCO[43] (Weatherall et al., 2015) and NOAA's Global Multi-Resolution Topography (GMRT)[44] (Ryan et al., 2009), are improving bathymetric resolution, and the integration of various data sources in global bathymetric models enhances our understanding of the shape of the seafloor. However, higher-resolution bathymetric data is still needed, particularly in regions where currents converge and where varying topographies significantly contribute to complex deep convection processes and Ocean mixing (see Figure 4.6). In addition, boundary layer dynamics, or the interaction between deep-sea currents and the seafloor, which is important to understand sediment transport and nutrient dynamics, remains underexplored (Ferrari et al., 2016).

41 https://seabed2030.org/our-mission/
42 https://seabed2030.org/
43 https://www.gebco.net/data_and_products/gridded_bathymetry_data/
44 https://www.ncei.noaa.gov/maps/bathymetry/



Credit: unpublished data by Sven Petersen, GEOMAR

Figure 4.5 Bathymetric maps of the Trans-Atlantic Geotraverse (TAG) on the Mid-Atlantic Ridge with increasing resolution from right to left: (A) General Bathymetric Chart of the Oceans (GEBCO) map based on satellite observations (1:150 000), (B) map based on a ship's (1:75 000), and (C) on AUV 400 Hz multibeam bathymetry (1:37 500).



Credit: Lars H. Rüpke, GEOMAR

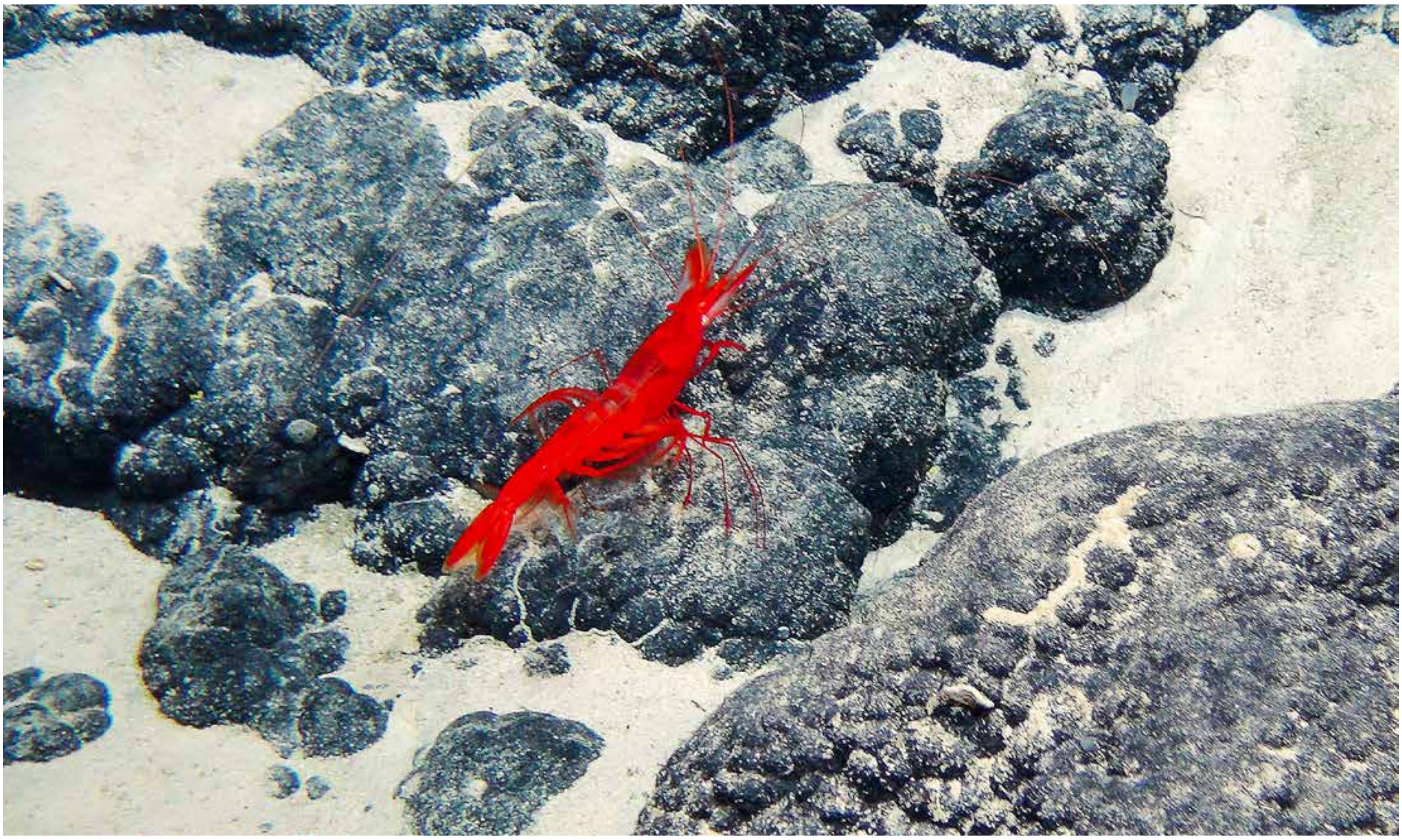
Figure 4.6 How bathymetric data coverage contained in the GEBCO bathymetry compilation has improved between 2014 and 2023 with a resolution of around 500 m. The GEBCO compilation provided a coverage of around 15% of the global seafloor in 2014. Data source: GEBCO https://www.gebco.net/data_and_products/historical_data_sets/

Bathymetry is key to understanding circulation patterns and regional and global Ocean-atmosphere processes and climate change. Uneven seafloor bathymetry controls near-bed thermohaline-driven currents, forming extensive seafloor sediment accumulations (contourites)[45] along continental margins. Recent studies in the Mediterranean Sea show that contourite drifts formed by bottom currents and controlled by spatial variations in current intensity linked to bathymetry have the highest microplastic concentrations reported for any seafloor setting (Kane et al., 2020). Dense, cold, bottom currents maintain their temperature and salinity, efficiently moving nutrients and oxygen between benthic habitats and influencing seafloor biodiversity. Insufficient characterisation of changes of these bottom currents signifies a gap in our knowledge, despite their significant impacts on deep-sea ecosystems and sediment transport processes.

Open Ocean upwelling occurs mostly at seamounts and mid-Ocean ridges (Mashayek et al., 2024), and are key contributors to Ocean mixing and global circulation; the so-called “conveyor belt” (Baker et al., 2023). However, mapping of the global distribution of seamounts is incomplete, as satellites can only detect seamounts taller than 2 km (Wessel, 1997). Recent advances in satellite technology have improved their accuracy, enabled the detection of smaller seamounts and expanding the global seamount catalogue (Gevorgian et al., 2023). Advances in satellite sensor technology and collaborative shipborne surveys are crucial to refining our understanding of the interplay between Ocean bathymetry, mixing, and bottom-layer processes, and their broader implications on climate, biodiversity, and pollution.

Seamounts and mid-Ocean ridges are intimately tied to the distribution of large populations of benthic organisms and pelagic top predators such as whales (Rovere & Würtz, 2015), making seamounts and mid-Ocean ridges hotspots of marine life. Mapping these habitats require multibeam bathymetry and seafloor backscatter calibrated with ground-truthing (seabed sampling), which is in turn essential for predicting benthic habitat and species distribution. For more information see the EMB Future Science Brief on Marine Habitat Mapping (Fraschetti et al., 2024).

National and international programs, such as Italy's Marine Ecosystem Restoration (MER) project[46], exemplify how Ocean mapping can aid Ocean protection. It aims to map seamounts and expand the network of Italian Marine Natura 2000 sites to 30% protected and 10% strictly protected areas[47] by 2026 to ensure the long-term survival of Europe's most valuable and threatened habitats. Seafloor mapping and sub-bottom profiling data are crucial for identifying areas needing protection, such as Vulnerable Marine Ecosystems (VMEs)[48] and potential future BBNJ Area-Based Management Tools, including Marine Protected Areas.



Credit: ROV-Team/GEOMAR

Shrimp at a seamount in the Clarion-Clipperton-Zone in the Central Pacific Ocean. The large biodiversity at seamounts is due to special currents: nutrients are retained by circulating currents near the top of the seamounts, and nutrient-rich water is carried up from greater depths by the currents surrounding the seamounts, which leads to increased plankton growth.

45 Flanders Marine Institute; Renard Centre of Marine Geology - Ugent (2019). Global contourite distribution database, version 3. Available online at https://www.marineregions.org/. https://doi.org/10.14284/346

46 https://www.isprambiente.gov.it/en/projects/sea/pnrr-mer-marine-ecosystem-restoration

47 https://www.snpambiente.it/snpa/ispra/la-nuova-conoscenza-del-mare/

48 https://www.fao.org/in-action/vulnerable-marine-ecosystems/en/

Comprehensive seascape data, including water column backscatter, sound velocity, conductivity, temperature, turbidity, redox and current data, are essential for identifying geothermal activity layers, hydrocarbon seepage, salinity changes, dissolved particles, and habitat variations. The global carbon cycle contribution from natural seepage of greenhouse gases, particularly at hydrothermal vents and cold seeps, is greatly overlooked due to limited high-resolution data (Rovere et al., 2022). Efforts to compile historical data and advance big data management and processing (see EMB Future Science Brief on Big Data in Marine Science (Guidi et al., 2020), combined with monitoring programs, are vital for expanding global seascape knowledge (Riedel et al., 2018). Detecting fluid seeping is now recognised as a precursor to earthquakes and a diagnostic that will potentially be integrated into future earthquake warning systems (Philip et al., 2023).

Future investments in emerging and innovative sectors of the Blue Economy, including interconnected offshore infrastructures and marine renewable energy platforms, will add further stressors to offshore and open-sea environments (see Section 5.3). The deployment of these infrastructures needs accurate data for defining location suitability in terms of the geological and geotechnical characteristics of the substrate, for example for anchoring the new deep sea floating wind power platforms (> 800 m water depth) and the occurrence of marine geohazards. Despite ongoing research, the occurrence and potential impacts of marine geohazards across Europe is a significant knowledge gap. Uncertainties remain, particularly in deep water, concerning the risks these hazards pose to human activities, infrastructure, and the marine ecosystem (see EMB Position Paper on Marine Geohazards, Kopp et al., 2021).

Exact acoustic measurement of deep-sea bathymetry is required for numerical forecasting models of tsunami propagation and coastal surges (Mayer et al., 2018), which threaten low-lying coastal communities, where 40% of the present world's population live. Tsunami propagation is influenced by water depth, with waves travelling faster in deeper waters (Satake, 1988). However, large portions of the deep sea remain inaccurately mapped. For instance, GEBCO data still miss major underwater features and have errors in depth measurements of hundreds of metres. Accurate and high-resolution bathymetric data are crucial for predicting tsunami impacts and planning for flood prevention, as precise bathymetry can determine prediction of the severity and location of tsunami hits, improving coastal safety and survival.

4.5 Deep-sea spatial and temporal variability gaps

Although once thought to be relatively stable and homogeneous, studies have revealed that deep-sea temperature, oxygen, pressure, currents, and tides vary substantially in space (both horizontally and vertically) and time. Oceanographic processes such as upwelling, downwelling and eddies play a significant role in shaping these patterns, affecting nutrient transportation and sedimentation rates (Johnson et al., 2024), with a direct link with the Ocean carbon cycle. Geological phenomena like volcanoes at mid-oceanic ridges or subduction zones also strongly affect the deep-sea environment, changing (sometimes in days) the seafloor substratum or the chemical composition of the surrounding water.

Deep-sea variability exists at many spatial and temporal scales, which are crucial to consider when linking structures and functions (Swanborn et al., 2022). Some gradients are displayed over small distances e.g. a few micrometres such as the nutrient concentrations available to bacteria (Stocker & Seymour, 2012), or a few centimetres such as for temperature near hydrothermal vents, while others span hundreds of kilometres, e.g. bottom-water temperature at the abyssal plains. Temporal variability of environmental parameters can also occur in seconds (e.g. mixing zones at hydrothermal vents), intra-daily (e.g. tidal effects) to decades (e.g. El Niño–Southern Oscillation). Spatially, the coarse scale variability (~ km) is relatively well known in the water column and at the seafloor thanks to remote sensing technologies and other monitoring methods implemented from the surface (e.g. fishing, dredging, sonar surveys). Time series data provided by observatories and long-term moorings (see for example EMSO network[49]) help to unravel the temporal variability in an environment (Glover et al., 2010). At finer scales (e.g. daily and weekly changes at metre-scale of bottom currents that influence organisms' dispersion), very little is known, and extensive high-frequency and high-resolution surveys are needed to improve our understanding of the impact that geophysical parameters have on the biology.

The high spatio-temporal variability in physico-chemical conditions generates many biological responses and adaptations, that creates a diversity of ecosystems, some of which were only discovered 40 years ago (Ramirez-Llodra et al., 2010). Thus, biological gradients should be considered in addition to physico-chemical gradients. For instance, in active hydrothermal vents or cold-water seeps, strong physico-chemical gradients structure the communities from fluid-exit habitats to peripheral areas (Gollner et al., 2010). Pelagic and benthic seamount communities are spatially structured by depth-related oxygen gradients and the temporal variability of oxygen distribution and community structure are tightly entangled (Ross et al., 2020). In comparison, abyssal plains are characterised by smaller spatio-temporal variability due to less extreme and less variable environmental conditions, although few studies have been devoted to these patterns (Pape et al., 2017). However, mesoscale variability (few kilometres) has been reported recently due to sedimentation processes (Durden et al., 2020). Similarly, in abyssal nodule-bearing regions, some sessile organisms are entirely dependent on the polymetallic nodules and are absent from the surrounding soft sediments (Vanreusel et al., 2016).

Although we are beginning to understand the structure and functioning of some deep-sea ecosystems, we do not have enough information to understand the complexity of their resilience to disturbances or interactions with other environments. The life cycles of most deep-sea organisms are poorly described, although larval dispersion and individual behaviours and tolerances to

[49] https://emso.eu/observatories/#overview

A mosaic of sponges and deep corals (*Madrepora oculata*) on a rocky drop-off in the Lacaze-Duthiers canyon, at a depth of 274 m, taken by the HROV Ariane during the CALADU campaign.

environmental stressors are key to predicting future changes in the deep due to anthropogenic disturbance and potential impacts. Similarly, understanding deep-sea physical processes is very important for understanding habitat connectivity and resilience mechanisms. However, when developing regional models (such as digital twins), physical processes like bottom currents or small-scale eddies are not yet systematically considered (Fox-Kemper et al., 2019), preventing accurate understanding of the environmental dynamics, which are critical to enable use of these models for future management. Combining observatories and autonomous underwater vehicles enables the study of spatio-temporal variability while retaining fine resolutions (see Box 1), but this requires substantial financial resources and human efforts.

To improve our understanding of ecosystem structure and functioning in the deep sea, we must increase our research capacity towards a more integrative approach across space, time and all ecosystem components. We need to survey in all environments but particularly in those studied the least, such as abyssal plains, seamounts, mid-Ocean ridges, canyons and trenches, pelagic systems, and take samples at a much higher spatial and temporal resolution to bridge this gap. Long-term monitoring is an important component to tackle these research gaps. Matabos et al. (2022) have suggested strategies on how monitoring can support and inform policies that can impact society. Such investments will be crucial if we want to predict the response of deep-sea environments to climate change and other anthropogenic activities and its effects on regulating services and biodiversity loss.

4.6 Blind spots in deep-sea management and governance

A fundamental blind spot in deep-sea management and good governance is the lack of baseline knowledge. Knowing the baseline conditions and the status quo is essential to track and understand (future) Ocean changes and mitigate effects on ecosystem function and services. Informed decision-making, as highlighted in many international instruments, is only possible with sufficient knowledge of baseline conditions and environmental problems associated with overlooking indirect, unintentional, or slow-to-occur consequences of human activities or "distant management" (Diamond, 2011). For deep-sea activities like mining, the weaknesses of exploration regulations, the many outstanding issues of the currently developed exploitation regulations (Pickens et al., 2024) as well as insufficient

Credit: IISD/ENB - Pam Chasek

BBNJ Family Photo. State delegations celebrating the adoption of the BBNJ Agreement at the Fifth Session of the Intergovernmental Conference (IGC) on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ), concluded at the UN Headquarters in New York on 20 June 2023. This marks the start towards ratification and implementation of the Agreement.

robust baseline data (Amon et al., 2022), and the uncertainty about the extent of impacts, prevent conclusive Environmental Impact Assessments (EIAs) and evidence-based management of deep-sea mining (Guilhon et al., 2022).

Any uncertainties in (environmental) baseline knowledge necessitate the careful implementation of the precautionary principle. This principle is aligned with the obligations under UNCLOS to protect and preserve the marine environment (Art. 192) and to prevent, reduce, and control marine pollution (Art. 194 and seq.), as is also stated in Article 7(e) of the BBNJ Agreement. In addition, States must avoid transferring damage or transforming one type of pollution into another (Art. 195 UNCLOS and Art. 5 (l) BBNJ). Article 194(1) of UNCLOS imposes stringent requirements, called "due diligence standard", given the high risks of serious and irreversible harm to the marine environment by human activities. Article 194(5) obliges States to protect and preserve rare or fragile ecosystems as well as the habitat of depleted, threatened, or endangered species and other forms of marine life. This unequivocally applies to rare and fragile ecosystems from the deep sea impacted by marine pollution, climate change and Ocean acidification.

Another blind spot is the lack of political will and coherence in implementing existing laws, as well as the inability to adapt management and governance structures in response to evolving environmental, socio-economic, and political conditions (e.g. competition over resource availability). While the Law of the Sea permits the consideration of certain changing circumstances related to the marine environment (Heidar, 2020), decision-makers are often (too) slow to recognise and address the profound and irreversible impacts of climate change across varying spatial and temporal scales. This includes the effects on the marine environment (e.g. Ocean acidification and deoxygenation) and broader societal impacts (e.g. extreme oceanic events). Recent developments have clarified that UNCLOS States Parties bear a specific obligation to protect and preserve the marine environment from climate change and Ocean acidification. These developments include the ongoing work of the International Law Commission on sea-level rise[50] and the advisory opinion by the International Tribunal for the Law of the Sea (ITLOS), which confirmed that anthropogenic greenhouse gas emissions into the atmosphere constitute marine pollution, which guide the actions of States moving forward[51]. Additionally, ongoing discussions about the Ocean and climate change have strengthened the linkages between Ocean governance and climate policy[52]. This dialogue addresses the future of the deep sea in a changing climate, although the focus has primarily been on the impact of climate change on coastal and marine ecosystems, blue carbon, and the conservation of biodiversity beyond national jurisdiction, with only peripheral focus on deep-sea ecosystems (Dobush et al., 2022). Addressing the complex issues affecting the Earth system in the Anthropocene will require systemic political, institutional, and cultural shifts[53].

[50] https://legal.un.org/ilc/summaries/8_9.shtml

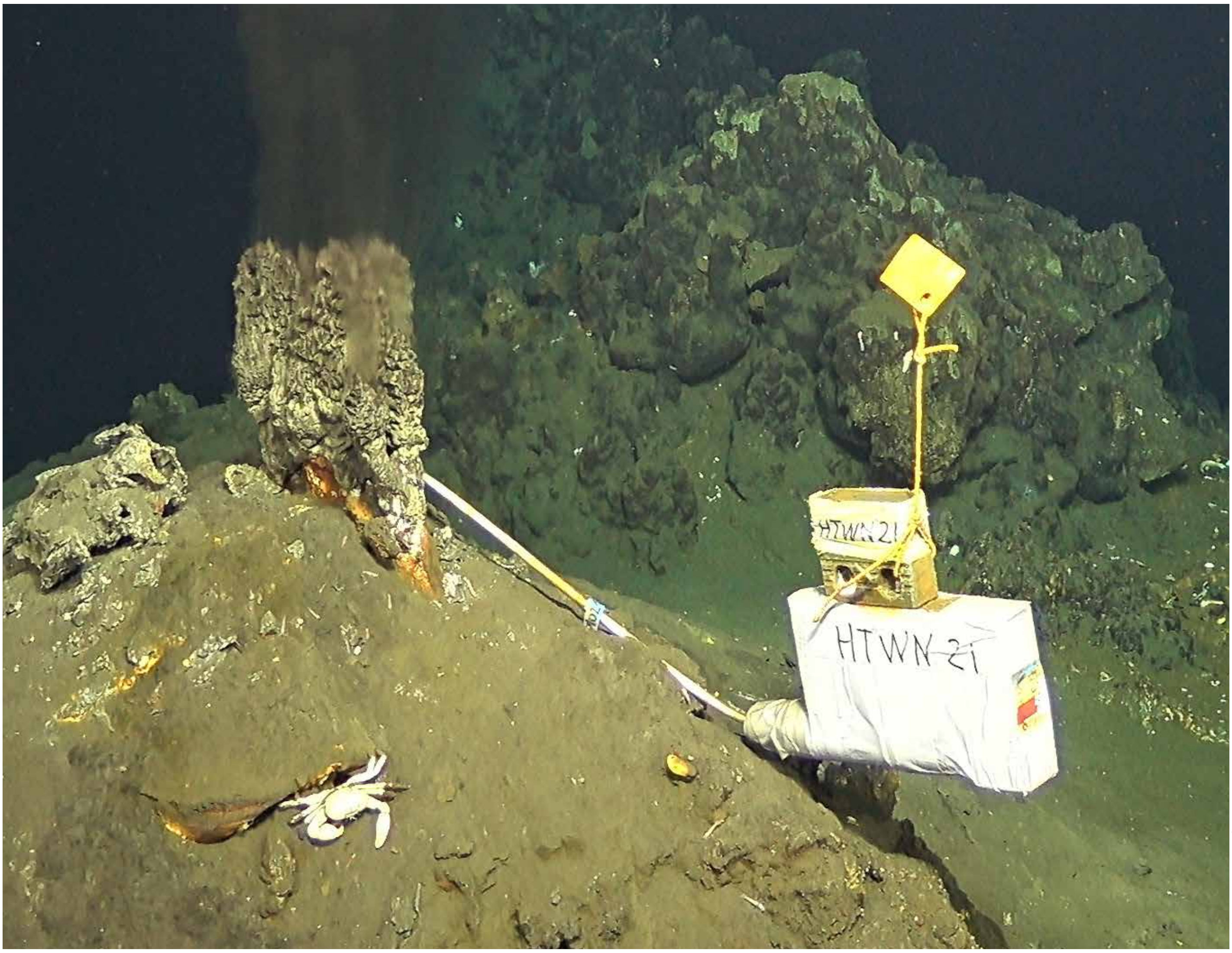
[51] Advisory Opinion in Case No 31, Request submitted to the ITLOS by the Commission of Small Island States in Climate change and International Law (COSIS), 21st May 2024: Advisory Opinion of 21 May 2024

[52] https://unfccc.int/topics/ocean/ocean-and-climate-change-dialogue

[53] https://www.earthsystemgovernance.org/

Problem-shifting[54] between socio-ecological systems and legal regimes regularly occurs in deep-sea management and governance due to the functioning of these complex systems. Problem-shifting is defined as abrupt or slow changes that can degrade one complex system while managing another (Kim & van Asselt, 2016). For example, due to climate change, fish populations migrate into deeper waters, leading fishing fleets to shift from depleted coastal areas to vulnerable deep-sea areas. This shift can lead to overexploitation of deep-sea species and damage their habitats, potentially undermining conservation efforts in these deep-sea areas. Problem-shifting can also result from political choices, where secondary effects are known or anticipated (Kim & van Asselt, 2016). The closer the interactions (e.g. Ocean, biodiversity, climate), the higher the risk of shifting problems between legal regimes. For instance, marine Carbon Dioxide Removal may be effective in the short-term as a solution for climate change mitigation, but does not guarantee long-term Earth system integrity, potentially exacerbating issues like Ocean acidification (Levin et al., 2023). The BBNJ Agreement specifically requires *"the non-transfer, directly or indirectly, of damage or hazards from one area to another and the non-transformation of one type of pollution into another in taking measures to prevent, reduce and control pollution of the marine environment"* (Art. 7 l). This obligation, amongst others, could help prevent and mitigate environmental problem shifting (Kim, 2024).

Finally, an overarching problem is the insufficient implementation of good global governance, which is detrimental to the health of the deep sea and of the Ocean in general. Good governance principles, such as transparency, accountability, participation, consensus orientation, rule of law, effectiveness, efficiency, equity, inclusion, sustainability, strategic vision, and ethical conduct, are not always respected. When the BBNJ Agreement is fully implemented by States and non-state actors, it will offer future opportunities to foster a good "holistic" Ocean governance in ABNJ.



Credit: Riwan Leroux, Ifremer, cruise Momarsat 2024

The monitoring of the Aisics chimney from the Tour Eiffel edifice at the Lucky Strike hydrothermal vent field (near the Azores) at 1,688 m depth. The temperature of the black smoker's fluid is monitored throughout the year with an autonomous probe to detect changes in hydrothermal activity. Baseline knowledge is essential for deep-sea management and good governance.

[54] In international law, problem-shifting refers to the practice where efforts to solve or mitigate a problem in one area inadvertently create new problems or exacerbate existing issues (such as pollution, damage or hazards). In order to avoid such shifting, there are so-called non-transfer clauses (Art. 195 UNCLOS and Art. 7 (l) BBNJ).

5 Our Ocean, our future, our responsibility

Many human activities continue to harm the Ocean, jeopardising vital ecosystem functions (Figure 5.1). The need for global, sustainable Ocean management and protection is globally exemplified by the adoption of a political declaration entitled "Our Ocean, our future, our responsibility"[55] by the United Nations Ocean Conference (UNOC) in July 2022. Diverse frameworks and bodies (see Chapter 2) govern the many deep-sea industries and uses. The ISA, who has the mandate to ensure the effective protection of the marine environment from harmful effects that may arise from deep-seabed-related activities, is currently working towards finalising exploitation regulations for deep-sea mining, although there are still many outstanding regulatory issues (Pickens et al., 2024). The 2023 BBNJ Agreement, once in force, will address the significant challenge of balancing the protection of marine biodiversity and its sustainable use in ABNJ. In accordance with UNCLOS, the BBNJ Agreement acknowledges the importance of cooperation for the conservation and sustainable use of marine biodiversity (see Chapter 2). However, given the significant scientific gaps in deep-sea knowledge (see Chapter 4), and the increasing anthropogenic pressures (this Chapter), major investments in deep-sea research and in capacity building are needed to provide science-based advice to inform critical policy decisions, to maintain a sustainable relationship between humans and the deep sea, and thus a healthy Ocean. Legally and institutionally, a healthy Ocean relies on the rule of law, the protection of a free public debate and the guarantee of human rights (including the right to science as recognised in Article 27 of the Universal Declaration of Human Rights of 1948)[56].

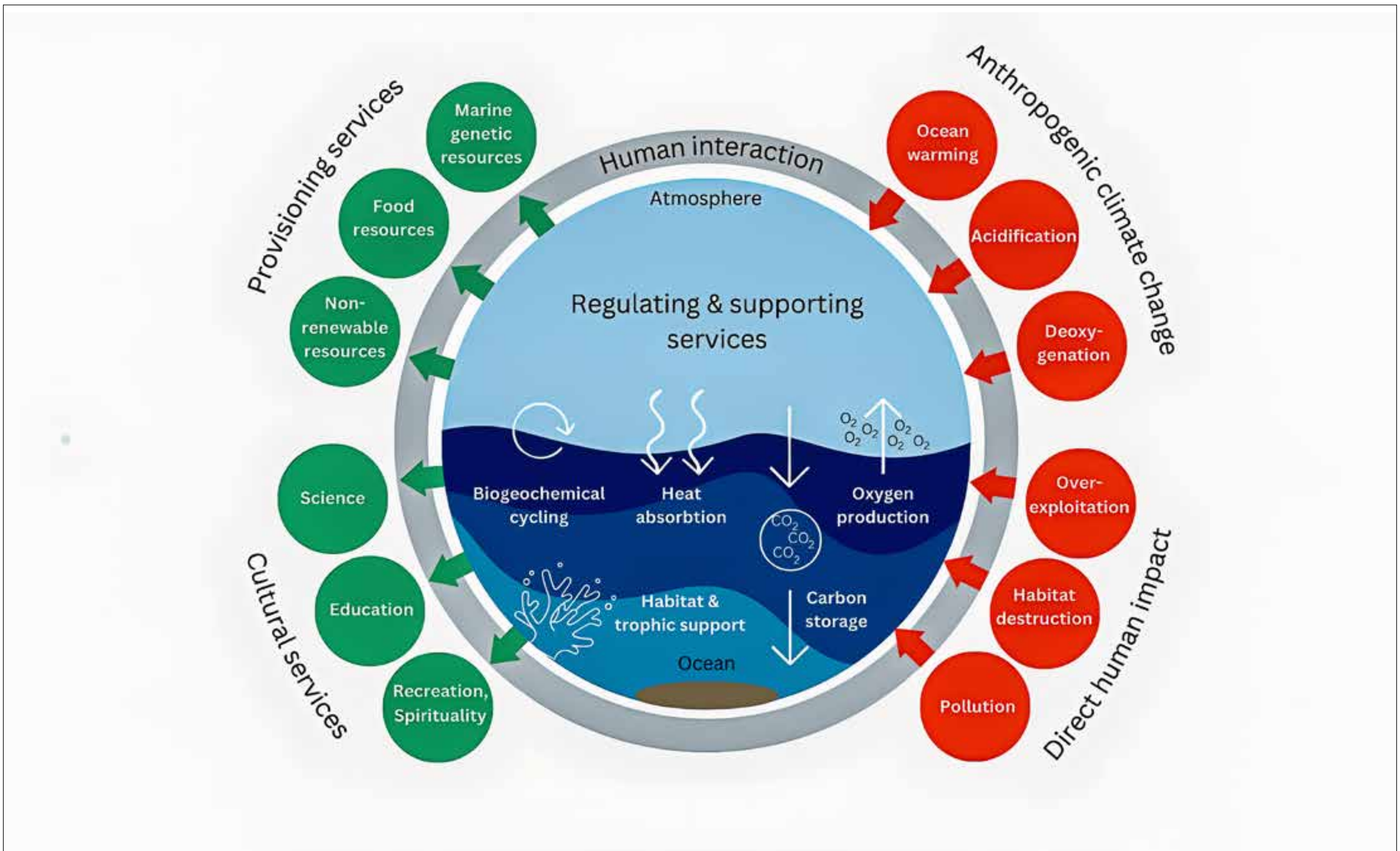


Figure 5.1 The regulating, supporting, provisioning and cultural ecosystem services provided by the Ocean (green and blue backgrounds), as well as the threats the Ocean is experiencing because of human activities such as (indirect) anthropogenic climate change and direct impacts including overexploitation, habitat destruction and pollution (red background).

55 https://sdgs.un.org/sites/default/files/2022-06/UNOC_political_declaration_final.pdf

56 Universal Declaration of Human Rights | United Nations. See also Art. 15(2) of 1966 International Covenant International Covenant on Economic, Social and Cultural Rights, UNGA Resolution 2200A (XXI) adopted on 16 December 1966: International Covenant on Economic, Social and Cultural Rights | OHCHR

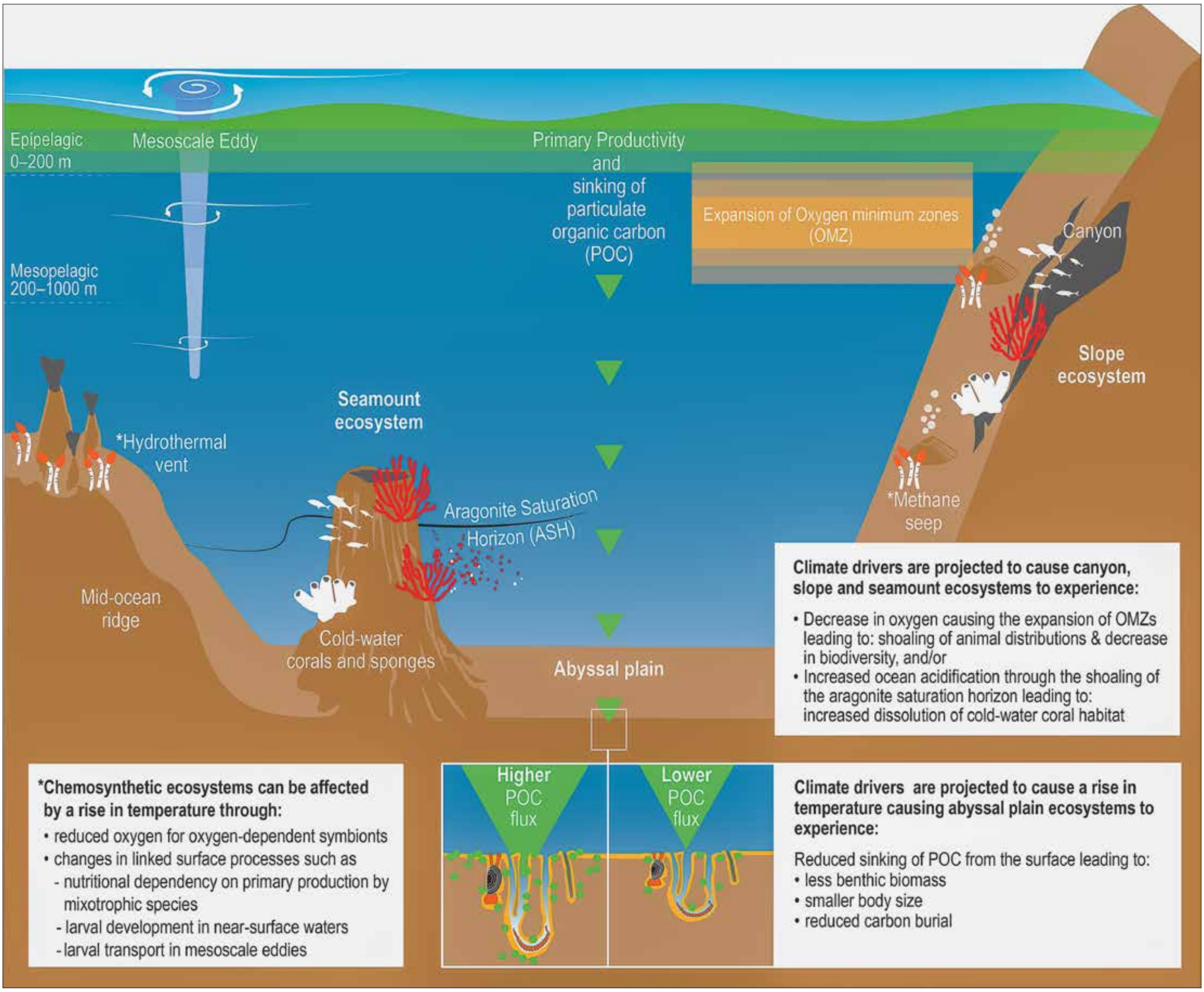


Figure 5.2 A conceptual diagram illustrating how climate drivers will modify deep-sea ecosystems (Figure 5.15 in the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, Bindoff et al., 2019).

5.1 Deep-sea health at risk: anthropogenic climate change

Because most deep-sea ecosystems depend largely on surface production, climate change effects on surface processes will alter deep-sea ecosystems globally, as is already evident in some areas (Figure 5.2). Climate stressors will compromise crucial ecosystem services provided by deep-sea ecosystems. The absorption of heat and CO_2 by the deep sea buffers climate change but also exposes vulnerable deep-sea ecosystems to cumulative and synergistic effects of warming, changing currents, acidification, deoxygenation, and altered food inputs.

From 1970 to 2010, the open Ocean lost 0.5 to 3.3% of its oxygen in the top 1,000 m, and oxygen minimum zones expanded by 3 - 8%, with deoxygenation also affecting deeper waters (Bindoff et al., 2019). Due to the slow exchange of deep and surface waters and reduced Ocean circulation in a more stratified Ocean, deep-sea deoxygenation is expected to persist for centuries, even after achieving net-zero greenhouse gas emissions, significantly impacting deep-sea ecosystems (see EMB Future Science Brief on Ocean oxygen, Grégoire et al., 2023).

Increased sea surface temperatures enhance water stratification, reduce vertical mixing and potentially limit the nutrients needed for phytoplankton growth, thereby altering the carbon pump and affecting nutrient cycling in the deep sea. By 2100, temperatures at abyssal depths (3,000 – 6,000 m) could increase by 1°C, and water-column oxygen concentrations will decrease by up to 3.7% or more (see EMB Future Science Brief on Ocean oxygen, Grégoire et al., 2023), affecting the flux of organic matter to the seafloor (Sweetman et al., 2017).

At bathyal depths (i.e. between 200 m and 2,000 m) pH will be significantly reduced (by between 0.29 to 0.37 pH units), altering surface plankton community structure, which in turn can influence the degradation of sinking particles and the efficiency of the biological carbon pump (Stange et al., 2018) or cause increased dissolution of calcium carbonate ($CaCO_3$) minerals at the deep seafloor (e.g. Sulpis et al., 2018), affecting the fitness and survival of calcifying organisms, such as sea stars and deep-sea corals.

Under current climate change scenarios, the projected increase in temperature, acidification, and decrease in oxygen in the deep sea will harm the metabolism of deep-sea organisms, because deep-sea species are adapted to typically cold temperatures, with low energy supply and have reduced metabolism (Danovaro et al., 2017b). The climate effects will affect growth rates, survival, and recruitment of deep-sea organisms, and will consequently change deep-sea ecosystems substantially (Levin et al., 2023). Hotspots of pelagic species such as tuna or krill, that are crucial for food webs, are expected to move due to cumulative exposure to future biogeochemical changes (e.g. Amon et al., 2023). The response of deep-sea life to these global changes will depend on these organisms' ability to adapt rapidly to altered conditions and maintain their biological interactions. Therefore, expanding knowledge of their biology—from physiology and symbiotic interactions to the factors controlling food webs and dispersal—is crucial.

The 6th IPCC Assessment Report indicates “low confidence” in our knowledge related to the deep sea and highlights major climate-relevant knowledge gaps. Most “low confidence” statements in the report were not explained and resulted from either a limited number of available studies or a lack of observations. An analysis of critical climate-relevant deep-sea science gaps have provided actionable recommendations for tackling uncertainty in seven major areas, such as the Ocean carbon cycle and climate change impacts on primary production, and recommendations for future IPCC reporting (Trossman et al., 2024).

5.2 Deep-sea health at risk: direct human impacts

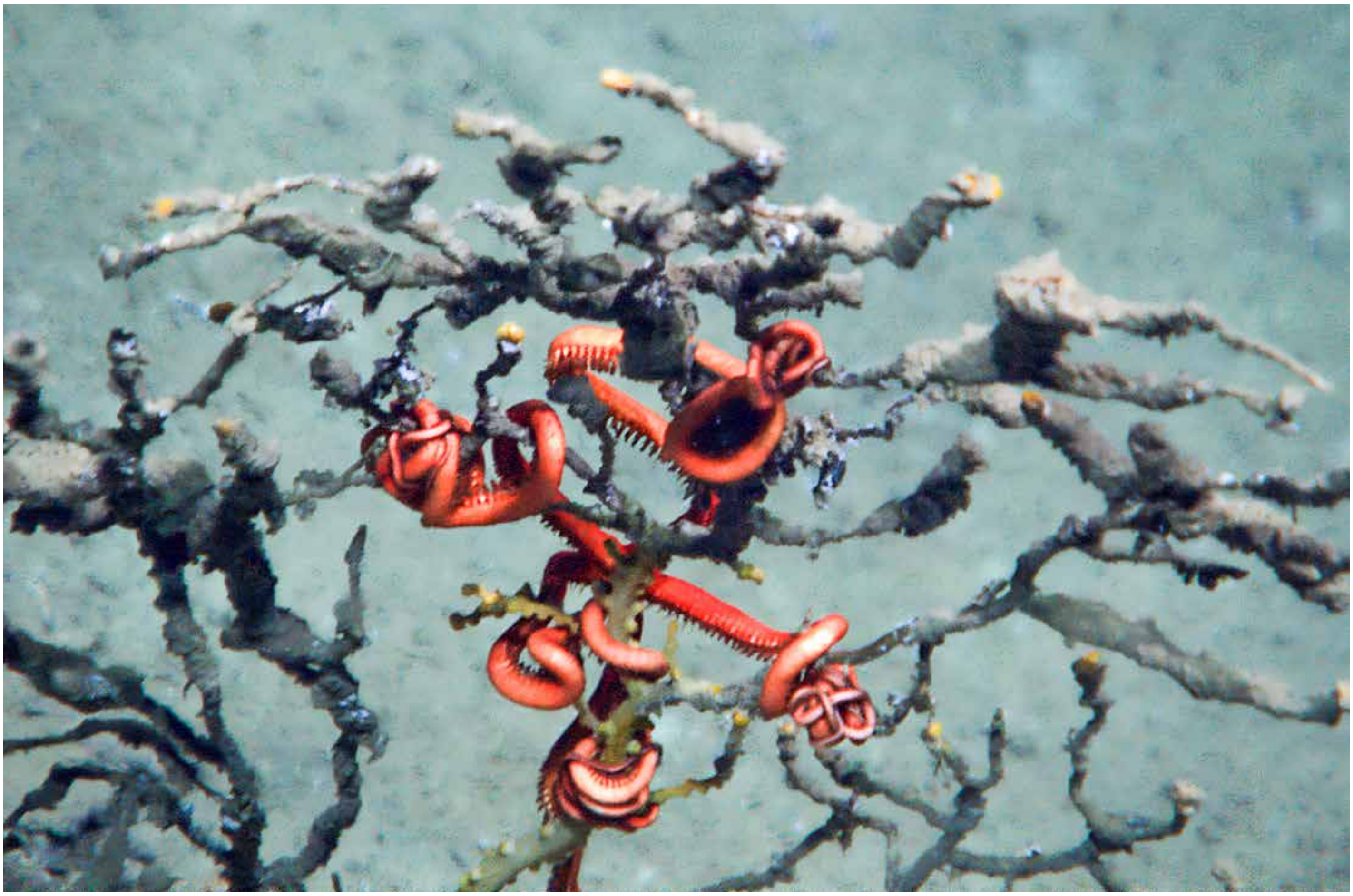
Direct human impacts such as the overexploitation of renewable and non-renewable resources, habitat destruction, and pollution affect deep-sea species which are typically long-lived, late reproducing, and have low fecundity.

Deep-sea fisheries reflect the expansion of human activities into remote environments, such as the mesopelagic (or twilight) zone. Deep-sea fishing takes place at great depths, between 200 and 2,000 m, on continental slopes, seamounts and ridges, and target demersal and benthic species. Deep-sea fish stocks are highly vulnerable to fishing due to their late maturity, low productivity and low fecundity. Thus, they can collapse rapidly and are very slow to recover. The Regional Fisheries Management Organisations (RFMOs), which are the existing management framework for high seas fisheries, cannot effectively manage deep-sea species and ecosystems, as they lack scientific knowledge, have limited implementation of ecosystem-based management approaches, and do not undertake environmental assessments (Wright et al., 2020). In addition, the most prevalent deep-sea fishing technique is bottom trawling, which causes major and long-term habitat destruction to the seafloor, seamounts and other vulnerable deep-sea ecosystems (Victorero, 2023). Trawling removes deep-sea coral colonies, which can be hundreds to thousands of years old (Roberts et al., 2005) and provide nursery and breeding grounds for the same species that are targeted by fisheries (Clark et al., 2015). The UN General Assembly resolutions of 2006[57] and 2009[58] called on States not to authorise bottom trawl fishing in deep-sea areas until measures have been put in place to avoid significant adverse effects such as habitat destruction, but these measures remain unimplemented. The EU also has legal measures to reduce the impacts of bottom trawling, including a ban on trawling below 800 m, and the closure of certain sensitive areas between 400 – 800 m depth within EU waters[59].

Offshore oil and gas industries directly impact deep-sea health, for example by causing noise, vibrations, or depositing by-products. The risk of accidents with consequences for the environment also increases with depth. The Deepwater Horizon blowout in the Gulf of Mexico in 2010 demonstrated the increasing range of environments in which extraction occurs, but also the ecological ramifications of accidents in the deep sea. The Deepwater Horizon oil spill caused significant damage to long-lived coral colonies: a complete recovery of the ecosystem and its services may require hundreds of years (Girard & Fisher, 2018). The impact of the Deepwater Horizon oil plume also impacted mesopelagic fish, and the pelagic predators linked to the mesopelagic food web (Morzaria-Luna & Ainsworth, 2022). Enacted in the aftermath of Deepwater Horizon, the EU Offshore Directive[60] aims to increase safety and reduce risk of offshore oil and gas operations. Many large offshore European hydrocarbon installations are due to be decommissioned in the next two decades. However, in the Mediterranean and Black Sea, offshore hydrocarbon exploration fields are only now being studied for viability. This implies that although the European Green Deal presumes a reduction of hydrocarbons in the energy sector and a transition to a clean, circular economy, it may not happen at the same pace in areas outside of EU-managed waters. Thus, although Europe is transitioning to become the first climate neutral continent by 2050, attention should still be given to the safety of existing and emerging operations in the carbon-based industry inside and outside of Europe and in trans-boundary areas, as the impact of any spills in these areas will still affect European waters. This requires trans-boundary research including an ecosystem-based approach, and technology and knowledge-transfer (OECD, 2016).

Human activities, including shipping, sonar, and drilling, have significantly increased underwater noise; a trend expected to continue with the expansion of future deep-sea industries. Elevated Ocean noise impacts marine communities in various complex ways, such as causing hearing loss, stress responses, habitat displacement, and disruption to feeding, breeding/spawning, nursing, and communication. Additionally, climate change will alter sound levels due to changes in seawater temperature and chemistry, further complicating the acoustic environment of the deep sea. EMB's Future Science Brief N°. 7 on Underwater Noise summarises current understanding and identifies future research priorities (Thomsen et al., 2021).

57 United Nations General Assembly (UNGA) (2006) UN Doc A/RES/61/105 https://docs.un.org/en/A/RES/61/105
58 United Nations General Assembly (UNGA) (2009) UN Doc A/RES/64/72 https://docs.un.org/en/A/RES/64/72
59 https://Oceans-and-fisheries.ec.europa.eu/fisheries/rules/deep-sea-fisheries_en
60 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32013L0030



Deep-sea coral affected by Deepwater Horizon oil spill, likely dead despite orange branch tips, with a brittle starfish attached.

Pollution from land-based sources, industrial activities and shipping, such as (micro)plastics, heavy metals, radionuclides[61], and chemicals, can all reach and impact the deep sea (Ramirez-Llodra et al., 2011), and can have harmful impacts on deep-sea organisms and ecosystems. Little is known about the resilience of deep-sea organisms to pollutants or their ability to provide services such as degradation of plastics or contaminant removal (Gui et al., 2023). In combination with climate change related stressors, these effects become even more unpredictable (Hatje et al., 2022). A working group from the Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) is currently investigating the climate change and GHG related impacts on contaminants in the Ocean[62].

5.3 Deep-sea health at risk: future industries

Whilst the deep sea is already impacted by many anthropogenic stressors including climate change, it is also often seen as a solution for climate change. This is problematic, as the consequences for Ocean health of future industries are often (if not always) unknown, putting natural ecosystem functions and services at risk (De Jager et al., 2021). The degree of impact varies depending on the type of industry and how it is managed (Bravo et al., 2023): it could be minor, as with marine genetic resource extraction, but the impact could also be permanent, as with resource removal (e.g. deep-sea mining).

Deep-sea mining poses a significant threat to deep-sea ecosystems (Niner et al., 2018). Tests have shown that it results in habitat destruction and the release of sediment plumes at the bottom but also in mesopelagic waters, impacting marine life (Gollner et al., 2017). Mining could lead to the loss of major ecosystem services, such as those provided by the microbial community, including primary production (Orcutt et al., 2020). Gaps in our knowledge of the scientific baselines and issues in the draft exploitation regulations would at this moment not allow for effective management (Pickens et al., 2024). As society depends on metals such as cobalt, nickel, manganese and copper, it may seem attractive to extract minerals such as polymetallic nodules, polymetallic sulphides and cobalt-rich ferromanganese crusts from the deep sea, leading to accelerated deep-sea mining. However, there are also calls for a moratorium and/or ban on mining in the Area[63] illustrating the division of the international society over the future of common resources. In parallel, within national jurisdiction, deep-sea mining developments follow their own domestic rules and speed, as is shown by the case of Norway that plans to mine their deep sea as soon as 2030[64].

[61] Mainly from nuclear waste, bomb testing, etc.
[62] GESAMP working group 45: Climate Change and Greenhouse Gas Related Impacts on Contaminants in the Ocean http://www.gesamp.org/work/groups/wg-45-ghg-impacts-on-contaminants-in-the-Ocean
[63] https://deep-sea-conservation.org/solutions/no-deep-sea-mining/momentum-for-a-moratorium/
[64] https://www.regjeringen.no/en/aktuelt/public-consultation-of-the-first-licensing-round-for-seabed-minerals/id3047008/

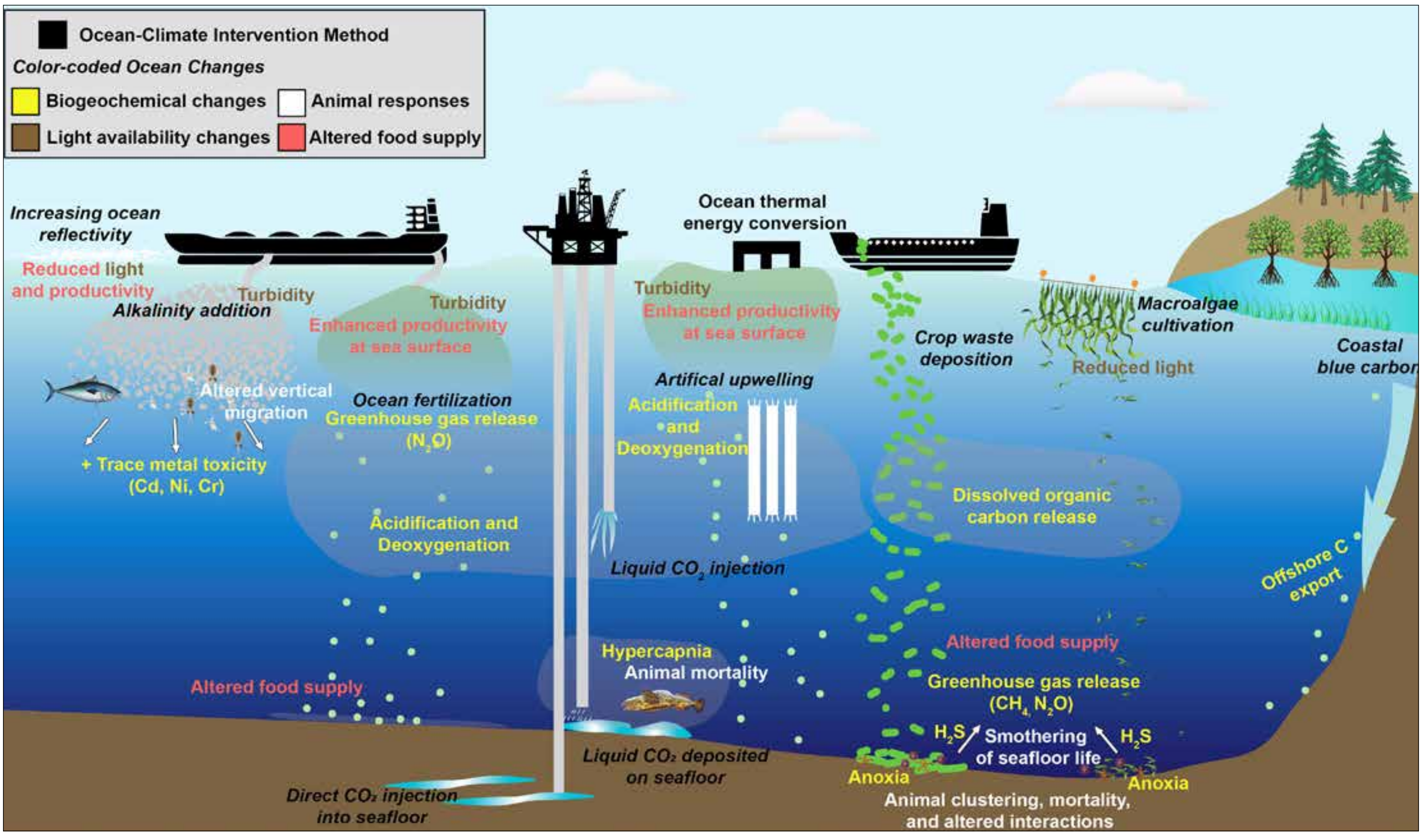


Figure 5.3 Several concepts for Ocean-Based Climate Interventions, including mCDR, along with their corresponding impacts on Ocean environments.

Although we understand the impact of some offshore renewable energy industries (see the EMB Future Science Brief on Offshore Renewable Energy, Soukissian et al., 2023) others such as wave energy, thermal energy conversion, green hydrogen or biofuels (mainly planned in waters shallower than 200 m), are less mature. This results in a high scientific uncertainty about their potential impacts on ecosystem services both in shallow water, where they are typically installed, as well as in the deep sea. Since offshore renewable energy may provide solutions to reduce human carbon emissions, it will be important to understand the potential trade-offs between positive outcomes due to the reduction of emissions mitigating climate change impacts, and the potential negative impacts of their installation and operation. It is not clear how the installation and operation of these devices will impact ecosystems in the long term, i.e. by changing species composition or facilitating invasive species, or what the knock-on effects might be on deep-sea ecosystems (e.g. changes in nutrient availability). Ideally, this trade-off analysis should therefore follow an ecosystem-based management approach (Bravo et al., 2023).

Similarly, marine Carbon Dioxide Removal (mCDR) methods might also impact the deep sea (Figure 5.3). There are currently tests to upscale different mCDR techniques, such as Ocean alkalinity enhancement experiments[65], which aims to speed up the Ocean and seafloor's ability to remove atmospheric CO_2 by adding alkaline material to seawater, while reducing Ocean acidity. For mCDR techniques to be successful, i.e. by removing enough CO_2 from the atmosphere and storing it in the deep sea to counteract CO_2 emissions, the chemistry and biology of the Ocean needs to be transformed. In addition to global impacts, more regional and local effects may occur, such as depletion of oxygen as a consequence of decaying plant matter or seaweed on the seafloor, or alteration of microbial activity which may harm species targeted by fisheries (Levin et al., 2023). The safety of this process is still very uncertain, and the monitoring, reporting and verification of this process is the topic of a European Marine Board working group that will make their recommendations in due course[66]. Any CO_2 effects on marine organisms will have ecosystem consequences; however, no controlled ecosystem experiments have been performed in the deep sea and therefore the large-scale impacts are still unknown (Boyd et al., 2023).

Activities linked to Marine Genetic Resources (MGR) involve the utilisation of any material of marine plant, animal, microbial or other origin containing DNA of actual or potential value (Art. 2 CBD; Art. 1(8) BBNJ) and of Digital Sequence Information (DSI) of these MGRs. This includes genetic material and sequence information that rare or endemic deep-sea organisms may carry, enabling them to produce a wide range of biochemicals that may also benefit humankind. These benefits could be accrued in pharmaceutical compounds, cosmetics, food supplements, research tools, and in industrial processes (Rogers et al., 2021). For instance, the antiviral drug Remdesivir used to treat COVID-19 draws on genetic information extracted from sea sponges[67]. Targeted, responsibly harvested, *in situ* samples of marine species for marine scientific research will probably have a limited effect on the marine environment, whilst offering the potential of fair and equitable sharing of benefits (Blasiak & Jouffray, 2024).

[65] https://www.geomar.de/en/discover/ocean-for-climate-protection/carbon-uptake-in-the-ocean/ocean-alkalinity-enhancement
[66] https://www.marineboard.eu/marine-carbon-dioxide-removal
[67] https://www.maripoldata.eu/governing-knowledge-in-relation-to-marine-genetic-resources-and-covid-19-vaccines/

Polymetallic nodules, polymetallic sulphides and cobalt-rich ferromanganese crusts. These mineral resources could be extracted from the deep sea to obtain metallic raw materials.

5.4 Restoration in the deep sea

Restoration is seen as one of the solutions to the effects of human impacts, as acknowledged for example by the ongoing UN Decade of Ecosystem Restoration[68] or the EU Nature Restoration Law[69]. However, deep-sea ecosystems are typically characterised by long lived organisms (e.g. fish that live for more than a hundred years, corals more than thousands of years) that reproduce late, so community recovery after disturbance is typically very slow. These long temporal scales, as well as the knowledge gaps on biodiversity and ecosystem functions of deep-sea ecosystems (see Chapter 4.1), present challenges for deep-sea restoration. Decades of monitoring will be needed to study the effectiveness of restoration actions (Da Ros et al., 2019). For example, frequent monitoring for 10 years after the Deepwater Horizon oil spill suggested that corals would take at least 50 years to recover, if they recover at all (Girard et al., 2019). Effective deep-sea restoration requires that policymakers and managers understand that restoration in the deep sea is a very slow, costly process (DOSI, 2024a). The costs of deep-sea restoration are estimated to be two to three orders of magnitude greater than restoration costs in shallow-water marine systems (Van Dover et al., 2014). Considering these costs, timelines and uncertainties associated with deep-sea restoration, preventing harm must be the preferred option (DOSI, 2024b).

5.5 Cumulative and synergistic impacts

Ecosystems and communities are never affected by one impact only. For example, climate change, noise and pollutants may have already affected a fish before it was caught. Coral communities that have been impacted by trawling may experience delayed recovery because of climate change. Whilst cumulative effects are the sum of all impacts, a synergistic effect occurs when the combined impacts are greater than the sum of individual impacts. Very little is known about cumulative and synergistic impacts in the deep sea, although the importance of considering these effects is well recognised. In addition, current studies tend to investigate the reaction of species to extremes (e.g. large concentrations of microplastics), while little is known about their reaction to moderate exposure of several environmental changes (e.g. small concentrations of microplastics in a slightly warmer environment). Recently, JPI Oceans[70] published a handbook produced by a group of experts on how to implement cumulative effects assessments (Melaku Canu et al., 2024), which should also be implemented in the deep sea.

68 https://www.decadeonrestoration.org/
69 https://environment.ec.europa.eu/topics/nature-and-biodiversity/nature-restoration-law_en
70 https://www.jpi-oceans.eu/en/cumulative-effects-human-activities

Credit: Alfred-Wegener-Institut, OFOS, Melanie Bergmann

Marine litter on the seafloor in Molloy Deep, the deepest point of the Arctic Ocean (5,500 m).

5.6 Deep-sea management and governance

As anthropogenic impacts in the deep sea will continue and likely increase, a standardised and robust set of methods and metrics are needed to monitor the baseline conditions and anthropogenic and climate change-related impacts on biodiversity, ecosystem functions, and ecosystem services. An ecosystem-based management approach that includes the detection and monitoring of ecosystem services in space and time (4D approach), with open access to baseline data from multiple sectors, will improve our global capacity to manage the deep sea (Bravo et al., 2023). FAIR data, sample specimens that are curated in trusted domain repositories, standardised Environmental Impact Assessments (EIAs), efficient global area-based management tools, and effective mitigation of harm will be required to maintain a healthy deep sea now and into the future.

The legal and institutional landscape with regard to deep-sea management and governance is fragmented (see Chapter 2). For marine areas beyond national jurisdiction and area-based management tools, the International Seabed Authority (ISA) has the mandate to ensure the effective protection of the marine environment from harmful effects that may arise from deep-seabed-related activities, and are therefore critical for the conservation of the seabed. The ISA is currently discussing the establishment of standardised approaches for regional environmental management plans (ISBA/29/LTC/8[71]; ISBA/19/LTC/8[72]) to ensure that their management measures are suitable to protect the marine environment from harmful mining impacts (Blanchard & Gollner, 2022). In addition, the ISA has an Action Plan for Marine Scientific Research in support of the UN Decade of Ocean Science for Sustainable Development[73] with six Strategic Research Priorities, such as advancing scientific knowledge and understanding of deep-sea ecosystems, and strengthening deep-sea scientific capacity.

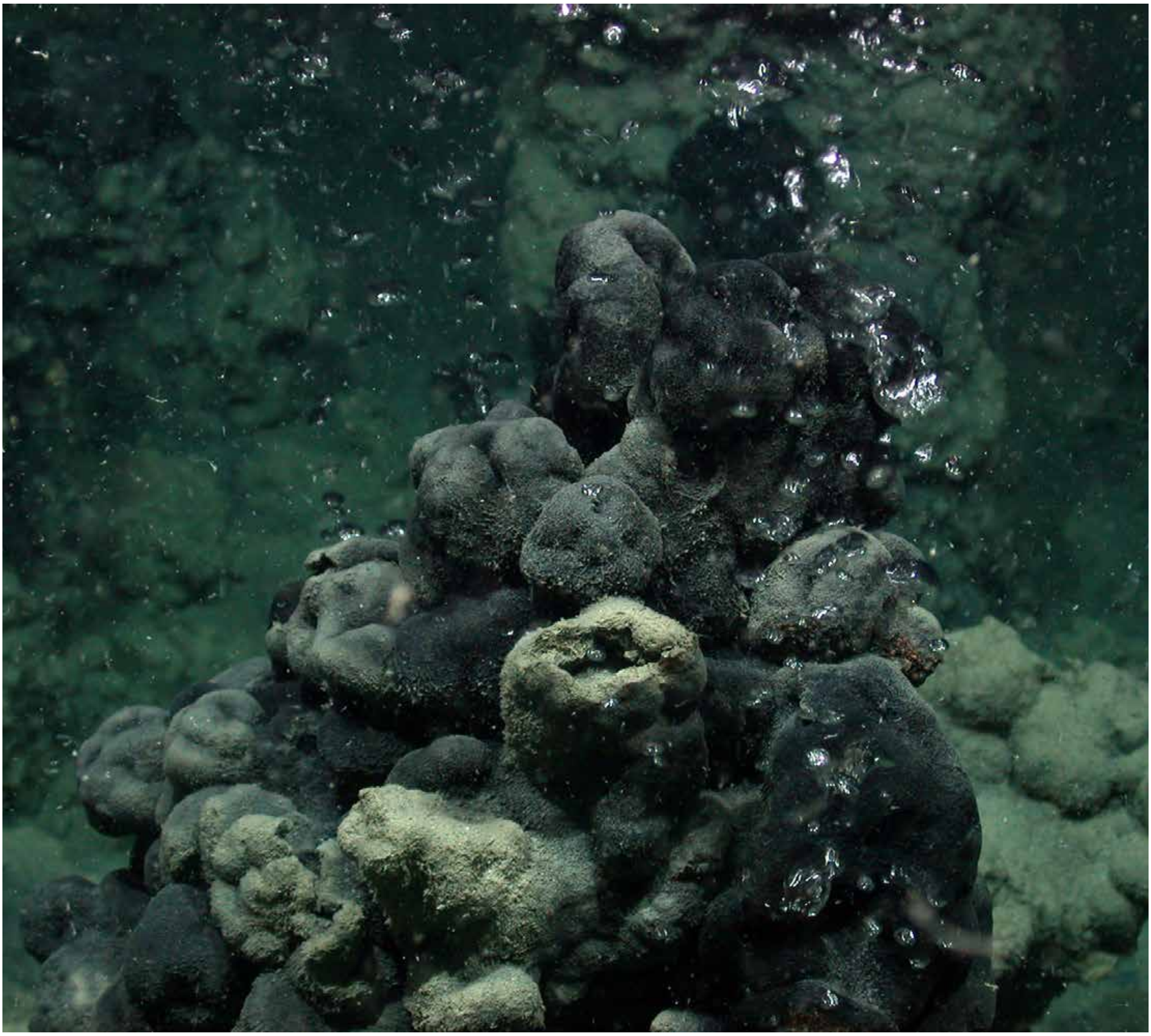
The BBNJ Agreement has the capacity to set standards and legal procedures for area-based management to efficiently conserve marine biodiversity and reach the goal of protecting 30% of the Ocean in Marine Protected Areas (MPAs, Goal D and Target 3 of the Kunming-Montreal Global Biodiversity Framework CBD/COP/15/L25)[74].

Currently only ~6% of the Ocean is protected[75], and it remains to be seen if 30% of global Ocean protection is sufficient to achieve a healthy Ocean. The BBNJ Agreement will also help to diligently conduct EIAs and to build capacity, transfer technology and collaborate with lesser developed countries that have an interest in Ocean health. However, how (and if) the BBNJ will improve

71 https://www.isa.org.jm/documents/isba-29-c-10/
72 https://www.isa.org.jm/documents/isba-29-ltc-8/
73 https://www.isa.org.jm/publications/isa-action-plan-for-marine-scientific-research/
74 https://www.cbd.int/conferences/2021-2022/cop-15/documents
75 https://mpatlas.org/

deep-sea health remains to be seen. In addition to the BBNJ, numerous other legal and policy means can enhance Ocean health, such as the Convention on Biological Diversity (CBD) and its Kunming-Montreal Global Biodiversity Framework, as well as the UN Ocean Decade (see Chapter 2). In addition, regional arrangements, such as the OSPAR Convention, can play critical roles to help to achieve a healthy Ocean. Particular attention is needed to ensure that the BBNJ Agreement is applied without undermining other relevant legal instruments, frameworks and relevant global, regional, sub-regional and sectoral bodies (see Figures 1.3 and 2.1), as well as to promote coherence and coordination with those instruments, frameworks and bodies (Art. 5(2) BBNJ; Singh and Jaeckel, 2024).

The EU has a comprehensive Ocean policy, framed within the EU Integrated Maritime Policy (IMP)[76] and the Marine Strategy Framework Directive (MSFD)[77], that aims to promote the sustainable use of the Ocean while protecting marine ecosystems. In addition, the recent European Ocean Pact initiative[78] seeks to foster a broader, integrated and holistic approach to Ocean governance across all sectors, including internal and external policies. The EU's approach to Ocean governance is largely guided by the principles of sustainability, environmental protection, and the sustainable Blue Economy. While there is no specific “deep sea” policy or law, various EU policies and regulations are relevant to the protection and sustainable management of the marine environment, including deep-sea ecosystems (Table 5.1).



Methane bubbles released at a carbonate chimney (or cold seep) 260 m below the surface of the Black Sea. Seeps can be indicators of shallow or deep hydrocarbon reservoirs. Under the EU Habitats Directive, cold seeps are listed as priority habitats, meaning EU Member States must take measures to protect and conserve them.

76 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52007DC0575
77 https://eur-lex.europa.eu/eli/dir/2008/56/oj/eng
78 https://oceans-and-fisheries.ec.europa.eu/news/shaping-european-oceans-pact-commission-launches-call-evidence-2025-01-20_en

Table 5.1 Main EU policies and laws relevant for the deep sea.

POLICY AREA	NAME	OBJECTIVES	RELEVANT ASPECTS
Fisheries	**Common Fisheries Policy (CFP)** (Art. 38-43 Treaty on the Functioning of the European Union)	Sustainable Management of EU fisheries within and beyond EU waters.	There are restrictions on fishing **deep-sea species** to prevent overfishing and protect Vulnerable Marine Ecosystems (VMEs), such as the prohibition of **bottom trawling** in areas that have been identified as hosting VMEs, such as cold-water corals and hydrothermal vents. Limits on **Total Allowable Catches (TACs)**, including deep-sea fish species (e.g. grenadiers, orange roughy, sharks).
	Deep-Sea Access Regulation (Regulation (EU) 2016/2336)	Manage and protect deep-sea fish stocks and ecosystems in the North Atlantic.	**Special fishing authorisations** to fish in deep-sea areas below 400 m. **Ban on bottom trawling below 800** m to prevent destruction of deep-sea habitats and protection of Vulnerable Marine Ecosystems (VMEs) from being impacted by deep-sea fishing activities. **Limitations on fishing effort** (e.g. number of vessels, hours spent fishing).
	EU Regulation on the Sustainable Management of External Fishing Fleets (Regulation (EU) 2017/2403)	Prevent illegal, unreported, and unregulated fisheries; Ensure transparency and accountability in the activities of EU vessels in non-EU waters; Promote sustainable fishing practices outside EU waters; Adhere to international agreements and RFMOs.	**EU vessels fishing in areas outside EU waters** (including deep-sea areas under international jurisdiction) adhere to high environmental standards and international agreements that protect marine ecosystems.
Environment	**European Green Deal** (COM/2019/640)	Achieve climate neutrality by 2050; Decouple economic growth from resources use; Protect biodiversity and ecosystems; Drive transformative change through research and innovation, etc.	The EU Green Deal indirectly impacts deep-sea areas by **reducing pressures from human activities and promoting marine conservation.**
Environment (Climate)	**EU Climate Law** (Regulation (EU) 2021/1119)	EU's goal of becoming climate-neutral by 2050, with a target of reducing emission by 55% by 2030.	This goal indirectly affects the marine environment by focusing on **reducing emissions from industries that impact the deep sea**, such as shipping, energy production, and resource extraction (including deep-sea mining).
Environment (Biodiversity and Nature)	**EU Biodiversity** Strategy for 2030 (COM/2020/380)	Legally protect at least 30% of EU's land area and 30% of EU's Sea area and integrate ecological corridors; Strictly protect at least one third of the EU's protected areas; Effectively manage all protected areas.	The strategy emphasises **the protection of marine ecosystems, including vulnerable deep-sea areas.** It calls for the **prohibition of destructive fishing practices,** like bottom trawling, which can significantly impact the deep sea.
	EU Nature Restoration Law (Regulation (EU) 2024/1991)	Long-term and sustained recovery of biodiverse and resilient ecosystems across Member States' land and sea areas through restoration of degraded ecosystems; Effective and area-based restoration measures with EU target to jointly cover at least 20 % of land and sea areas by 2030, and all ecosystems in need of restoration by 2050.	**Binding timely and quantitative targets for the restoration of marine ecosystems.** Member States shall ensure that there is an increase of the area in good condition for habitat types listed in Annex II which are not in good condition, including vents and seeps in the Atlantic, softs sediments (not deeper than 1,000 m) in the Atlantic, and the Baltic, Black and Mediterranean Seas.
	Habitats Directive (Directive 92/43/EEC)	Conserve natural habitats and wild species in the EU; Create a network of protected areas; Sustainable development; Monitoring and reporting.	**Natura 2000 network:** includes deep-sea habitats, particularly those featuring vulnerable ecosystems such as reefs, seamounts, and hydrothermal vents. **Annex I habitats:** Certain deep-sea habitats (e.g. reefs, submarine structures made by leaking gases such as cold seeps) are listed as priority habitats, meaning EU Member States must take measures to protect and conserve them.

POLICY AREA	NAME	OBJECTIVES	RELEVANT ASPECTS
Environment (Marine)	**Marine Strategy Framework Directive (MSFD)** (Directive 2008/56/EC)	Achieve "Good Environmental Status" (GES) for all EU marine waters by 2020 and beyond; Ensure marine environment is protected, conserved and sustainably managed.	**GES through qualitative Descriptor (D) 6: Seabed integrity** focusing on seafloor integrity including deep-sea ecosystems, aiming to ensure that their structure and functions are not adversely affected by human activities. D1 "Biodiversity", D3 "Fish and Shellfish population", D4 "Foodwebs", D8 "Contaminants", D10 "Marine litter" and, D11 "Underwater noise" are relevant for deep-sea biodiversity. **Protection and restoration of Vulnerable Marine Ecosystems (VMEs)** including deep-sea habitats (e.g. cold-water corals reefs, deep-sea sponges' aggregations, seamounts, submarine canyons, hydrothermal vents) by requiring EU Member States to assess the impact of human activities on these habitats and take actions to mitigate or reverse damage. **Monitoring** the status of EU Member States' waters, including the deep sea, **and assessment of progress toward** achieving GES. **Mitigation of human activities on marine ecosystems,** including the deep sea.
Energy	**Revised Renewable Energy Directive** (Directive EU/2023/2413)	Overall renewable energy target of at least 42.5% binding at EU level by 2030 – but aiming for 45%.	The Directive supports to the development of **offshore renewable energy,** including wind and wave energy projects, which can be in deep-sea areas. This includes provisions to streamline the planning and permitting processes for offshore renewable energy projects. **Environmental impact assessment** of renewable energy projects, including those in deep-sea environments.

In the fragmented landscape of deep-sea management and governance, and the silos of natural sciences disciplines, it can be challenging to advance integration of science, technology, policy, and law to optimise sustainable management of resource use and maintain the integrity of deep-sea ecosystems. It is imperative that there is clear communication between deep-sea science and policy to tackle the fragmentation of knowledge and to facilitate mutual understanding and collaboration on Ocean governance and science advancements. This is recognised in the EU International Ocean Governance agenda[79] that *"encourages creating an intergovernmental science-policy interface for Ocean sustainability, aiming at establishing an Intergovernmental Panel for Ocean Sustainability*[80] *(IPOS)*[81]*"*.

The EU Marine Strategy Framework Directive was established to protect the marine ecosystem and the biodiversity upon which our health and marine-related economic and social activities depend. Nevertheless, there is still no definition of "good environmental status" for the deep sea. The EU International Ocean Governance agenda fully acknowledges the importance of the Ocean, but recognition of the deep sea is currently rather limited, with the term "deep sea" only mentioned in relation to deep-sea mining. EU support for research is mainly focused on improving knowledge on deep-sea ecosystems and on monitoring deep-sea exploitation, but it is not clear how this will be achieved.

While there are notable instances where the EU is already taking steps with respect to deep-sea research, including funding Horizon Europe projects on deep-sea restoration (REDRESS[82] and DEEPREST[83]), as well as international efforts such as the ISA's Seabed Sustainability Knowledge Initiative (SSKI), there is still limited funding for topics addressing the many missing deep-sea baselines (see Chapter 4) and consequences of human impacts in the deep sea. The outcomes of gaps and recommendations of this Future Science Brief on the deep sea should feed into existing EU agendas.

79 https://oceans-and-fisheries.ec.europa.eu/publications/setting-course-sustainable-blue-planet-joint-communication-eus-international-ocean-governance-agenda_en
80 https://ipos.earth/
81 IPOS is currently being developed as the "International Platform for Ocean Sustainability"
82 https://redress-project.eu/
83 https://deep-rest.ifremer.fr/

5.7 Capacity building and Ocean literacy

Article 27 of the 1948 Universal Declaration of Human Rights states that *"everyone has the right freely to participate in the cultural life of the community, to enjoy the arts, and to share in scientific advancement and its benefits"*[84].Despite being enshrined in this declaration, the scope of science as a human right—and the obligations arising from it —remains unclear and underdeveloped[85]. The International Science Council interpretation[86] provides a framework for understanding the right to science and challenges what human rights pertain to the use of science. The BBNJ Agreement, as well as Challenge 10 of the UN Ocean Decade ("Restore society's relationship with the Ocean"), are excellent opportunities to promote science and put capacity building and marine technology transfer into practice. In addition, increasing the number of deep-sea experts and making good use of that expertise across disciplines and geographies will be essential for promoting deep-sea science and ensuring a healthy, well-functioning future Ocean. For example, no country has achieved gender equity. Female chief scientists on seagoing expeditions are still in the minority (Johannesen et al., 2022). Between 2021 and 2023, only 31% of chief scientists were female in France, while in Germany that falls to only 20%. Other examples of gender inequity include career development, first authorship, and large proposal applications (e.g. ERC grants) – this is called "the leaky pipeline" (Giakoumi et al., 2021).

Further action is required to ensure that deep-sea science becomes more equitable across regions (Figure 5.4). Currently European research institutes possess the necessary technology and human resources for deep-sea exploration and research, however, maintaining these resources is crucial. To remain competitive, we need to update current technologies and develop new instruments, which will require sustained technological investments. In addition, we need to maintain, strengthen, and renew the workforce as needed. European countries should also facilitate wider global access to deep-sea research (Bell et al., 2022). Nevertheless, co-designing scientific research and sharing capacities between global regions present significant challenges, therefore we need to learn from existing efforts and adapt them to create more collaborative, inclusive, and impactful research initiatives (Mahajan et al., 2023).

There are still large knowledge gaps in the fundamental understanding of processes in the deep sea (see Chapter 4), and on the applied questions of how to monitor environmental impacts of future industries or how to effective mitigate them. In addition, scientific knowledge must be openly communicated and shared across geographic regions and between people with different expertise, from science to policy to the public and *vice versa*.

A major hurdle to effective deep-sea management, and funding for deep-sea science, is the general lack of understanding of the benefits derived from the Ocean, and the deep sea in particular (Darr et al., 2020). A 1983 cartoon from The New Yorker, reflecting public opinion during the third United Nations Conference on the Law of the Sea, shows a character saying, *"I don't know why I don't care about the bottom of the Ocean, but I don't."* More than 40 years later, the deep-sea scientific community is still striving to make people care about the deep sea (Jamieson et al., 2021). Ocean literacy can help with that.

Ocean literacy involves understanding the Ocean's influence on humans and vice versa (Santoro et al., 2018). Ocean literacy efforts include not just teaching children, but also public outreach, citizen science, education, and lifelong learning as listed in the EMB Position Paper Delving Deeper: Critical challenges for 21st century deep sea research' (Rogers et al., 2015). Studies have shown that Ocean literacy approaches in deep-sea research projects can foster nature-centered attitudes and recognition of the need for sustainable management. For example, the Røst cold-water coral reef off the Lofoten Islands is well known in Norway due to an effective publicity campaign (Ankamah-Yeboah et al., 2020).

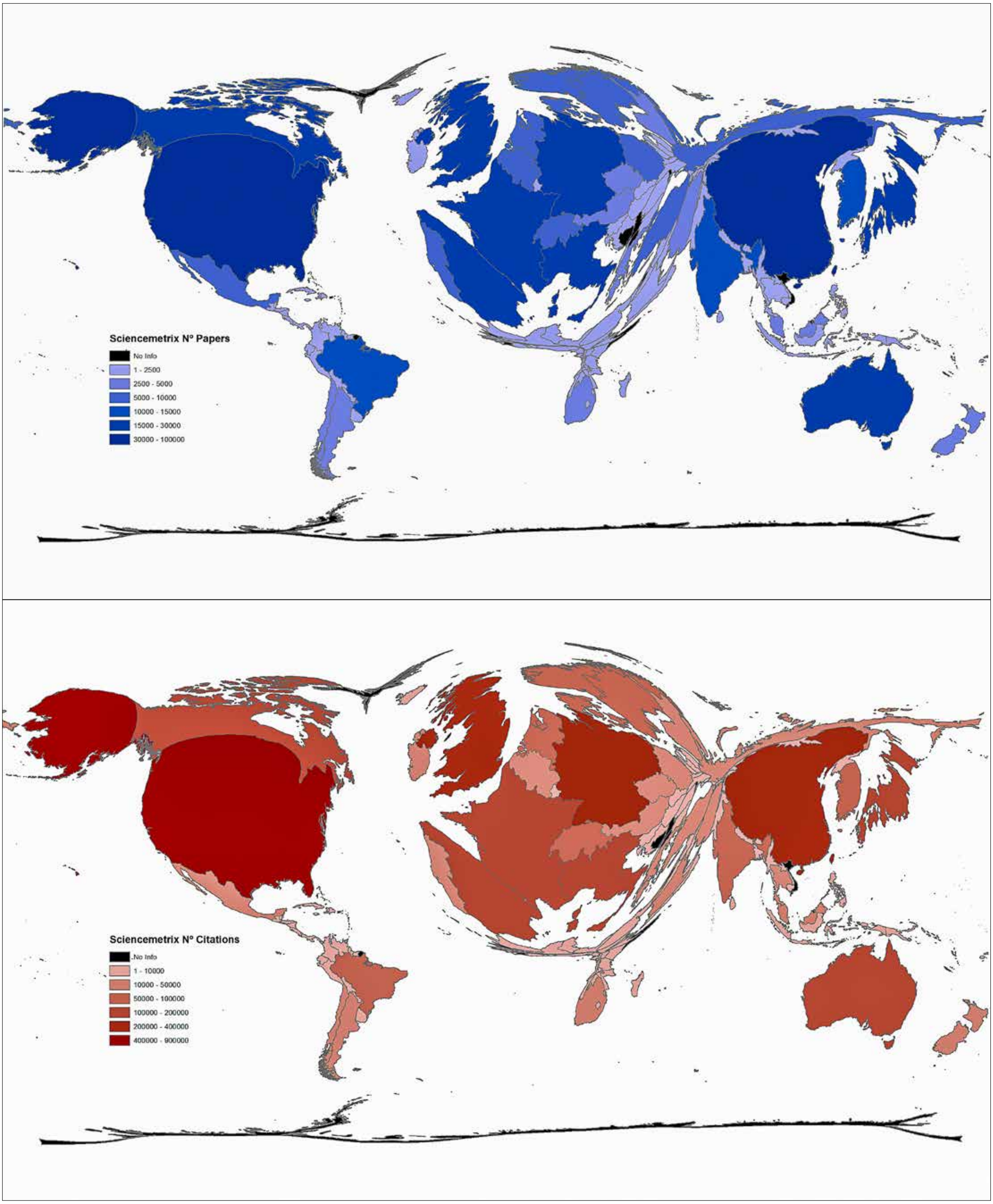
Credit: Melita Mokos

Primary school students participating in the workshop Sea of Light, Sea of Darkness (Zadar, Croatia) where they learned about life and environmental conditions in the deep sea, using hydrothermal vents as an example.

[84] Universal Declaration of Human Rights | United Nations. See also Art. 15(2) of 1966 International Covenant International Covenant on Economic, Social and Cultural Rights, UNGA Resolution 2200A (XXI) adopted on 16 December 1996: International Covenant on Economic, Social and Cultural Rights | OHCHR

[85] Besson S., Le droit international face à la distinction public/privé, Course nº. 2 of the "Droit international des institutions", Collège de France 22 February - 7 April 2022: https://www.college-de-france.fr/fr/agenda/cours/le-droit-international-face-la-distinction-publicprive

[86] https://council.science/our-work/right-to-science/



Credit: Global Ocean Science Report, ScienceMetrix, 2015 (UNESCO, 2017)

Figure 5.4 Map showing geographic inbalance in the production of Ocean science. The area of each country is scaled and deformed according to the number of Ocean science publications (top) and citations received (bottom). Different colours indicate a different number of publications (top) and citations (bottom).

6 Recommendations

The deep sea is underrepresented in policy considerations, and critical research needs are often overlooked. Despite its immense ecological importance and role in the ecosystem and climate, it is often neglected in global conservation and management efforts, while facing threats from unsustainable resource exploitation. To ensure a healthy present and future Ocean, evidence-based decision-making requires comprehensive, multidisciplinary baseline knowledge. Currently, 90% of all Ocean species remain undescribed, and many natural functions and services are not well understood, with the biggest knowledge gaps being in the deep sea. This lack of knowledge poses risks to the Ocean, Earth, and human health, which will be exacerbated by increased human activities in the deep sea and climate change. Effective management plans and regulations need sufficient scientific foundation and legitimacy. Europe should lead in implementing international measures to protect and effectively manage the deep sea and must also promote and support efforts in underrepresented countries and in areas beyond national jurisdiction.

Whilst acknowledging that the EU's International Ocean Governance Agenda and its Biodiversity Strategy already focus on protecting marine biodiversity, especially in the context of climate change, Ocean acidification, and pollution, by promoting Marine Protected Areas, ensuring sustainable fisheries, and supporting international agreements, like 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 (BBNJ Agreement), we urge that these agendas are put into action, with a focus on the deep sea. Therefore, Europe must take a more active and central role in leading international efforts to protect and sustainably manage the deep sea.

The following recommendations are addressed to the European research and innovation communities and stakeholders, as well as to European and Member State policymakers. These recommendations emphasise that the deep sea should be considered in a broader policy context and as a strategic dimension of International of Governance and EU policy, within and beyond areas of national jurisdiction. Recognising the interconnected nature of the deep sea (see Section 1.5), these recommendations address scientific, technological, economic, financial, and environmental issues, emphasising the need for all countries to understand the crucial role of the deep sea in Ocean (and human) health and the importance of capacity building, especially in scientifically underrepresented nations.

Public international institutions, such as the working groups from the Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO) programmes, UN Ocean Decade activities and the upcoming Scientific and Technical Body under the BBNJ Agreement (Art. 49), among others, should continue to promote science-policy communication and transdisciplinary research. They must provide advice, recommendations, and reviews to the agreement Parties and collaborate with other relevant legal instruments and bodies. The future BBNJ Conferences of Parties (COPs) will be crucial in promoting the sustainable use of the deep sea internationally, while we rely on EU and national laws to manage the waters within the EEZs. The BBNJ Agreement will only be effective if all countries have sufficient capacity and appropriate technology to enable effective participation in science and Ocean management. In the current geopolitical and climate change context, deep-sea areas could become areas of tension or conflict between States and stakeholders, at a time when international cooperation and multilateral action are more critical than ever to address the societal and ecological challenges of this century.

Recommendations for policy and management to sustain Ocean health for future generations:

The European Union (EU) and European nations should take an active role in leading international efforts to protect and sustainably manage the deep sea through:

(1) **Effectively governing human activities in the deep sea** within EU jurisdiction and in areas beyond national jurisdiction (ABNJ), in alignment with the BBNJ Agreement and relevant EU and international laws.

(2) **Establishing an international scientific committee for deep-sea sustainability and protection** to identify key areas to be monitored and protected, with the goal of reaching the Global Biodiversity Framework Target of 30% protection by 2030, and to be able to provide recommendations for funding essential scientific projects.

(3) **Contributing to develop and implement standardised deep-sea Environmental Impact Assessment methodologies** in order to understand and manage human impacts and the associated risks in the deep sea.

Recommendations for funders, research and monitoring, to increase our understanding of Ocean health over time and space:

National and European research funders should support research and monitoring to help close significant knowledge gaps in understanding Ocean processes and connectedness over space and time through:

(4) **Supporting transdisciplinary research programs to better understand the role of the deep sea in Ocean (and human) health.** This includes, but is not limited to, disciplines of natural sciences, social sciences and humanities, law, indigenous knowledge, engineering, and technology. These programs should aim for a holistic understanding of interactions between the deep sea, Ocean and planetary health.

(5) **Investing in long-term monitoring of the deep sea.** Long-term, regional, and basin-scale multidisciplinary monitoring programs need to be established, and existing ones should remain operational, to describe baselines, capture shifting baselines under climate change and other anthropogenic impacts, and ensure effectiveness of protected areas.

(6) **Launching large-scale and long-term multidisciplinary natural sciences projects to increase knowledge of global deep-sea processes.**

(7) **Supporting research efforts in specific critical research fields,** such as, but not limited to, advancing genomic sequencing and taxonomy, and increasing our knowledge on: (i) the metabolic consequences of species adaptation to climate change through experimental studies; (ii) cumulative and synergistic impacts on deep-sea species; (iii) the (mid-water) biological carbon pump, (iv) the rate of change of deep-sea temperatures; (v) the Meridional Overturning Circulation (MOC) and its impact on upwelling and downwelling processes; and (vi) abiotic and biotic subseafloor processes and their connectedness to Ocean processes.

Recommendations for global capacity building to better understand and manage the deep sea:

International cooperation and multilateral action should ensure that all countries have sufficient capacity and appropriate technology to actively engage in scientific research and Ocean management, in order to implement the 2023 BBNJ Agreement effectively. This may be achieved by:

(8) **Enhancing educational, training, and research opportunities for all current and future scientists addressing their unique regional challenges,** particularly those from underrepresented regions, as a way to implement science as a global fundamental human right.

(9) **Fostering the transfer of marine technology and developing training programs,** to increase the number of deep-sea research initiatives by underrepresented nations.

(10) **Continuing to promote the Findability, Accessibility, Interoperability, and Reusability (FAIR) Data principles.**

A more comprehensive list of Specific, Measurable, Attractive, Realistic and Time-bound (SMART) recommendations and their implementation is presented in the table on page 56.

RECOMMENDATIONS FOR POLICY AND MANAGEMENT TO SUSTAIN OCEAN HEALTH FOR FUTURE GENERATIONS

	RECOMMENDATION	OUTCOME	METRIC	SUGGESTED TIMELINE
1	**Effectively govern human activities in the deep sea** Target: the EU and European nations	Effective regulations addressing the impacts of human activities on deep-sea ecosystems in areas within (and beyond) EU jurisdiction and the Area have been implemented.	• Entry into force of the BBNJ Agreement and alignment of national policies.	• Within one year EU-wide ratification of the BBNJ Agreement. • Continuous efforts to enforce the BBNJ Agreement and align with national policies by 2030. • Continuous efforts to include deep sea in Ocean governance frameworks.
2	**Establish an international scientific committee for deep-sea sustainability and protection** Target: International science-policy initiatives (e.g. IPOS, DOSI, GESAMP, IOC/UNESCO)	An independent, multidisciplinary scientific committee with the task to provide advice on the sustainability and protection of deep-sea ecosystems to EU and international regulatory bodies has been established. Members participating in the International Platform for Ocean Sustainability (IPOS). Committee provides recommendations for funding essential scientific projects.	• Formation of the committee and launch of scientific projects to identify priority areas for deep-sea protection to promote Ocean sustainability within and beyond national jurisdiction. • Publication and reporting of results to the BBNJ Scientific Body, to the ISA and other relevant (inter-)national bodies. • Identification of areas to establish monitoring networks (see Recommendation 5).	• Committee established within one year. • Scientific projects for identification of protected areas and monitoring areas launched within 2nd year. • Identification of protected areas and monitoring areas by 2029, accounting for the "30 by 30" framework • Scientific projects for identification of possible sustainable uses of the deep sea launched within 2nd year.
3	**Contribute to develop and implement deep-sea Environmental Impact Assessment methodologies** Target: International science-policy initiatives (e.g. IPOS, DOSI), in collaboration with EU and international regulatory practices (e.g. BBNJ Agreement)	Effective impact and risk assessment, and monitoring methodologies for human activities in the deep sea have been developed and are being implemented.	• Creation of standardised environmental impact assessment protocols and integration of these protocols into EU and international regulatory practices	• Methodology developed within five years. • Methodology compliance required for new European Framework Programme project proposals. • Methodology integrated into regulatory practices within 10 years.

RECOMMENDATIONS FOR FUNDERS, RESEARCH AND MONITORING, TO INCREASE OUR UNDERSTANDING OF OCEAN HEALTH OVER TIME AND SPACE

	RECOMMENDATION	OUTCOME	METRIC	SUGGESTED TIMELINE
4	**Support transdisciplinary research programs to better understand the role of the deep sea in Ocean (and human) health** Target: National and European research funders e.g. though projects like GEOMAR's FUTURO[87]	Transdisciplinary research programs, including natural and social sciences and humanities, law, indigenous knowledge, engineering and technology have been launched and are operational.	• Funding and initiation of at least three major transdisciplinary research projects focused on deep-sea ecosystems and the role of the deep sea in Ocean and human health.	• Projects initiated within three years. • Initial findings published by the end of the Ocean Decade 2030.
5	**Invest in long-term monitoring in the deep sea** Target: National and European research funders e.g. through the European Ocean Pact[88]	Long-term, regional, and basin-scale multidisciplinary monitoring programs have been established to characterise the environmental baseline and continuously capture changes in deep-sea ecosystems. Data gained through long-term monitoring inform policies that can impact society, such as the effectiveness of protected areas.	• Strategies to measure, e.g. Essential Ocean Variables, and the needed technologies are in place, with data collection and analytical protocols standardised and implemented. • Existing long-term monitoring projects remain operational. • Deployment of at least three new long-term monitoring observatories in the deep sea in identified critical areas (see Recommendation 2).	• Projects initiated within three to five years. • Monitoring programs operational and baseline data available by 2030. • Integration of data from existing and new projects to inform policies by 2030. • First effectiveness evaluation of protected areas by the 10-year mark.

[87] https://www.geomar.de/en/futuro
[87] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/14474-The-European-Oceans-Pact_en

RECOMMENDATIONS FOR FUNDERS, RESEARCH AND MONITORING, TO INCREASE OUR UNDERSTANDING OF OCEAN HEALTH OVER TIME AND SPACE

	RECOMMENDATION	OUTCOME	METRIC	SUGGESTED TIMELINE
6	**Launch large-scale and long-term multidisciplinary natural sciences projects to increase knowledge of global deep-sea processes** Target: National and European research funders	Understanding of geological, physical, biological and biogeochemical deep-sea processes have been significantly advanced.	• Launch and funding of at least five multidisciplinary minimum 10-year-long natural sciences projects to increase knowledge of deep-sea processes. • Publication of at least 100 peer-reviewed papers enhancing knowledge of geological, physical, biological and biogeochemical deep-sea processes in our changing deep sea.	• Projects initiated within three to five years. • Continuous publication of findings throughout the lifetime of the projects.
7	**Support research efforts in specific critical research fields** Target: National and European research funders	Critical knowledge gaps in specific ecosystems and research disciplines have been filled.	• Invest in genomic sequencing and taxonomy to boost biodiversity research. • Fund projects on subject matter including, but not limited to, increasing our knowledge on: (i) the metabolic consequences of species adaptation to climate change through experimental studies; (ii) cumulative and synergistic impacts on deep-sea species; (iii) the (mid-water) biological carbon pump, (iv) the rate of change of deep sea temperatures; (v) the Meridional Overturning Circulation (MOC) and its impact on upwelling and downwelling processes; and (vi) abiotic and biotic subseafloor processes and their connectedness to Ocean processes.	• Continuous. • Subject matter to be updated by the Scientific Committee for Deep-Sea protection (see Recommendation 2).

RECOMMENDATIONS FOR GLOBAL CAPACITY BUILDING, TO BETTER UNDERSTAND AND MANAGE THE DEEP SEA

	RECOMMENDATION	OUTCOME	METRIC	SUGGESTED TIMELINE
8	**Enhance educational, training and research opportunities for all current and future scientists addressing their unique regional challenges** Target: International cooperation and multilateral action (e.g. IOC/UNESCO)	Implement science as a fundamental human right on a global scale.	• Launch of a platform or calls to fund co-designed research projects in underrepresented areas.	• Kick-off of the first call at the entry into force of the BBNJ treaty, and not later than 2026. • Continue efforts beyond the Ocean Decade.
9	**Foster the transfer of marine technology and develop training programs** Target: International cooperation and multilateral action at the framework of the BBNJ Agreement	Access to and use of marine technology in underrepresented nations improved.	• Transfer and implementation of advanced marine technologies and training programs, increasing the number of deep-sea research initiatives by underrepresented nations by 50%.	• Kick-off of technology transfer and training programs starting at the entry into force of the BBNJ treaty, and not later than 2026. • Continue efforts beyond the Ocean Decade.
10	**Continue to promote the Findability, Accessibility, Interoperability, and Reusability (FAIR) Data Principles** Target: International cooperation and multilateral action, in collaboration with Ocean data initiatives	Widespread adoption of the FAIR Principles.	• Integration of FAIR-compliant sample and data management systems in all European research institutions.	• 100% accessible and reusable deep-sea research samples and data by 2030.

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List of abbreviations and acronyms

4D	Four-dimensional
AUV	Autonomous underwater vehicle
BBNJ	Biodiversity Beyond National Jurisdiction
BCP	Biological carbon pump
CBD	Convention on Biological Diversity
CCZ	Clarion-Clipperton Zone
CFP	Common Fisheries Policy
CHM	Common Heritage of Mankind
CO_2	Carbon dioxide
CTD	Conductivity, temperature, depth
DOOS	Deep Ocean Observing Strategy
DOSI	Deep Ocean Stewardship Initiative
DSBS	Deep-Sea Biology Society
DSI	Digital Sequence Information
EBM	Ecosystem-based management
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessments
EMSO	European Multidisciplinary Seafloor and water column Observatory
ENSO	El Niño–Southern Oscillation
ERC	European Research Council
EU	European Union
FAIR	Findable, Accessible, Interoperable, Reusable
FAO	Food and Agriculture Organization
GBIF	Global Biodiversity Information Facility
GEBCO	General Bathymetric Chart of the Oceans
GES	Good Environmental Status
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
GHGs	Greenhouse gases
GMOC	Global Meridional Overturning Circulation
GMRT	Global Multi-Resolution Topography
HOV	Human Operated Vehicle
IMO	International Maritime Organization
INTERRIDGE	A non-profit organisation concerned with promoting all aspects of Ocean floor research (its study, use, and protection)
IOC-UNESCO	Intergovernmental Oceanographic Commission of United Nations Educational, Scientific and Cultural Organization
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPOS	International Platform for Ocean Sustainability

ISA	International Seabed Authority
ITLOS	International Tribunal for the Law of the Sea
IUCN	International Union for Conservation of Nature
LTER	Long-Term Ecological Research
mCDR	Marine Carbon Dioxide Removal
MGR	Marine genetic resources
MLD	Mixed Layer Depth
MOC	Meridional Overturning Circulation
MPA	Marine Protected Area
MRV	Monitoring, Reporting, Verification
MS	Member States
MSFD	Marine Strategy Framework Directive
mSRM	Marine solar radiation management
MVP	Moving Vessel Profilers
NGO	Non-governmental organization
NOAA	National Oceanic and Atmospheric Administration of the United States
OBCIs	Ocean-based climate interventions
OBIS	Ocean Biodiversity Information System
OECD	Organisation for Economic Co-operation and Development
OHCHR	Office of the High Commissioner for Human Rights
POC	Particulate organic carbon
RFMO	Regional fisheries management organisation
ROV	Remotely operated vehicle
SCOR	Scientific Committee on Oceanic Research
SDG	Sustainable Development Goal
SSKI	Seabed Sustainability Knowledge Initiative
TAC	Total Allowable Catch
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Climate Change
UNGA	United Nations General Assembly
UNOC	United Nations Ocean Conference
WOA	World Ocean Assessment
WOAH	World Organisation for Animal Health
WHO	World Health Organization
WorDSS	World Register of Deep-Sea Species
WoRMS	World Register of Marine Species
WWF	World Wildlife Fund

Glossary

Abiotic - Non-living components of an ecosystem or environment.

Abyssal plain - Underwater plain on the deep Ocean floor.

Abyssopelagic - Water layer of the Ocean between 4,000 and 6,000 m.

Anthropocene - The suggested geological age in which human activities are having a dominant influence on climate and the environment.

Autonomous Underwater Vehicle - Unmanned and autonomous vehicles that are deployed from vessels for survey missions at remote distances from the vessel.

Autotrophic - Organisms that can produce their own energy (i.e. food), also called primary producers.

Backscatter - Data on the intensity of sound waves released from echosounder devices reflected back from the seabed, used to measure substrate softness and texture.

Bathypelagic - Water layer of the Ocean between 1,000 and 4,000 m.

Benthic - Associated with or occurring at the seafloor.

Biological carbon pump - The Ocean's biologically driven sequestration of carbon from the atmosphere and land runoff to the Ocean interior and seafloor sediments.

Biome - Large naturally occurring community of species occupying a major habitat.

Box-corer - A device that retrieves a large physical sample of the uppermost layers of the seabed.

Canyon - A deep cleft between escarpments or cliffs resulting from weathering and the erosive activity of a water flow over geologic time scales.

Chemosynthetic - Organisms that use chemical energy, instead of light, water and carbon dioxide, to produce food.

Cobalt-rich ferromanganese crusts -A layer formed by precipitation of metals dissolved in seawater on rock substrates of volcanic origin. They occupy large areas on top of seamounts, ridges and plateaus.

Cold seep - Areas on the Ocean floor where gases percolate through underlying rock and sediment layers and emerge on the Ocean bottom.

Conductivity - A measure of water's capability to pass electrical flow, as a way to measure the salinity of Ocean water. Conductivity increases with the concentration of dissolved salts.

Continental shelf - The area of seabed around a large land mass where the sea is relatively shallow compared with the open Ocean.

Contourites - Sediments deposited or substantially reworked by the persistent action of Ocean-bottom currents.

Crawler - A robot that moves independently, carrying scientific instrumentation for scanning a continuous track of the seabed for prolonged periods.

CTD (Conductivity, Temperature and Depth)-rosette - A collection of seawater sampling bottles housed in a round frame, with instruments for measuring depth, temperature and conductivity of the water.

Cultural ecosystem services - Ecosystem services that provide non-material benefits derived from nature such as recreation and tourism, beauty, as well as spiritual, intellectual and cultural benefits.

Deep-sea cascading - Movement of surface waters to deeper depths down the continental slope.

Deep-sea convection - Movement of surface waters to deeper depths with large vertical velocities.

Deep-sea downwelling - Movement of surface water to deeper depths.

Deep-sea upwelling - Movement of deep water to the surface mixed layer.

Diel vertical migration - Upward migration of organisms towards the Ocean surface at night, and a downward movement to deeper waters in the daytime.

Detritivorous - Organisms that feed on dead and decomposing organic matter.

Dredge - A tool used for collecting samples from the seabed. It typically consists of a metal frame with an attached net or basket, which is dragged along the seabed to scoop up sediment, rocks and biological organisms.

Echosounder - A type of sonar used to map the seafloor and can be either single- or multi-beam.

Eddies - Circular current of water.

Endemic - Native and restricted to a certain place.

Epipelagic - Water layer of the Ocean between surface and 200 m.

Eukaryotic - Of, relating to, or being an organism with organelles and a membrane-bound nucleus.

Euphotic - Of, relating to, or constituting the upper layers of a body of water into which sufficient light penetrates to permit growth of phytoplankton, algae and/or photosynthetic microorganisms.

Fecundity - The ability to produce an abundance of offspring or new growth.

Float - A device that drift and measure Ocean currents, either at the surface or at a given depth.

Glider - A type of autonomous underwater vehicle that are deployed from vessels for survey missions at remote distances from the vessel. They typically do not have an engine, and instead use changes in buoyancy to move up and down through the water.

Gravity corer - A device that retrieves a physical sample of several meters of the uppermost layers of the seabed using the gravity of the drop from the vessel. These are mostly used in shallow waters.

Hadal trench - Prominent, long, narrow topographic depressions of the seabed in the deepest region of the Ocean.

Hadopelagic - Water layer of the Ocean deeper than 6,000 m.

Heterotrophic - Organisms that cannot produce their own energy (i.e. food), instead taking nutrition from other sources.

Human Operated Vehicle - A submersible that bring a small group of scientists, pilots, and electronic equipment down in the water column and onto the seafloor.

Hydrocarbon seepage - Emanation of reduced chemicals (e.g. hydrogen sulfide, methane) from the seafloor, supplied by subsurface hydrocarbon reservoirs.

Hydrothermal vent - An opening in the seabed out of which heated mineral-rich water flows.

Internal wave - A type of gravity wave that oscillate within internal “surfaces” of Ocean waters, rather than on the surface.

Isobaric sampler - A device created to keep organisms in an environment as close to their *in situ* conditions as possible during recovery from collection.

Lander - An observational platform that sit on the seabed or benthic zone to record physical, chemical or biological activity.

Lithosphere - The solid, outer part of Earth, composed of the crust and the topmost portion of the upper mantle.

Mesoscale eddy - An eddy with typical horizontal scales of less than 100 km and timescales in the order of a month.

Mesopelagic - Water layer of the Ocean between 200 and 1,000 m.

Metagenomes - The full genetic content of all the organisms within an environmental sample (e.g. eDNA).

Metagenomics - The study of genetic material recovered directly from environmental samples by sequencing.

Metatranscriptomics - A technique to study the gene expression of organisms within an environmental sample.

Metazoan - Multicellular organisms with cells that are differentiated into tissues and organs.

Mooring - A device connected to a wire and anchored to the seafloor, and which is stationary at a fixed location. These are used to measure Ocean currents.

Moving Vessel Profiler - A computer controlled winching system that can deploy and recover a sensor from a vessel that is underway.

Multibeam Echosounder - An acoustic device that uses sonar to map seabed bathymetry, morphological characteristics and substrate types.

Multicorer - A device that retrieves simultaneously several physical samples of the uppermost layers of the seabed and the overlaying bottom water.

Multinet - Equipment designed for quantitative sampling of plankton in successive water layers, and features a multiple net system.

Mid-Ocean ridge - Long, seismically active submarine ridge system situated in the middle of an Ocean basin associated with seafloor spreading.

Nekton - Organisms in the Ocean that are able to swim and move independently of water currents.

Optoacoustic - A technique that involve the generation of acoustic waves in a material induced by the absorption of light. Also referred as photoacoustic.

Pelagic - Associated with the water column.

Plankton - Organisms in the Ocean that are carried by tides and currents, and cannot swim well enough to move against these forces.

Polymetallic nodules - Rock concentrations on the seafloor formed of concentric layers of iron and manganese hydroxides around a core. Also known as manganese nodules.

Polymetallic sulphides - Mounds formed of metal sulphide mineral precipitates and hydrothermal vent debris.

Prokaryotic - Of, relating to, or being an organism without a nucleus and other organelles.

Provisioning ecosystem services - Ecosystem services that provide tangible, harvestable goods such as fish, shellfish and seaweed for food, raw materials, algae and minerals.

Redox reaction -The transfer of electrons between chemical species (i.e. atoms, ions or molecules) involved in the reaction. Also known as oxidation-reduction reaction.

Regulating ecosystem services - Ecosystem services that regulate natural processes and maintain ecological balance, such as coastal protection, prevention of erosion, water purification and carbon storage.

Remotely operated vehicle - An underwater platform equipped with sensors, cameras and/or manipulator arms remotely controlled from the surface via a cable.

Seamount - A submarine mountain.

Stratified Ocean - The natural separation of the Ocean water into horizontal layers by density.

Supporting ecosystem services - Ecosystem services that maintain fundamental ecosystem processes, such as photosynthesis or nutrient cycling, or the maintenance of genetic and biological diversity.

Tethered - Attached by a cable to a data or power source.

Annex 1

Members of the European Marine Board Working Group on Deep Sea and Ocean Health

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