Navigating the
Future VI

Placing the Ocean within the wider Earth system

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hcmr ΕΛΚΕΘΕ
Irish Marine Universities Consortium
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CoNISMa Consorzio Nazionale Interuniversitario per le Scienze del Mare

National Research Council of Italy
OGS National Institute of Oceanography and Applied Geophysics
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National Oceanography Centre

Navigating the
Future VI

Position Paper 28

Navigating the Future VI: Placing the Ocean within the wider Earth system
European Marine Board IVZW - Position Paper 28

This Position Paper is the result of the work of the European Marine Board Working Group on Navigating the Future VI. See Annex 1 for the list of Working Group Members and affiliations.

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October 2024

Foreword

The first iteration of Navigating the Future, published in 2001, called on the European community to work together to ensure that marine research is coordinated at a European level. However, the understanding of, and action on, the Ocean in the context of climate change was only proposed in 2015 during the 41st Session of the United Nations Framework Convention on Climate Change (UNFCCC). Subsequently, in September 2019, the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6), including a Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) was delivered. 2019 was also the year that Navigating the Future V was published, recommending that the marine research community should seek to break out of its traditional silos to work together across and beyond disciplines. We are now at the midpoints of the EU Framework Programme Horizon Europe, the EU Mission: Restore our Ocean and Waters, and the UN Decade of Ocean Science for Sustainable Development. Today, most policymakers understand that the Ocean is a critical element in a healthy world conducive to life, and its challenging exploration shapes our imagination and provides a source of innovation, just as much as the conquest of space.

Indeed, the Ocean forms a single, enormous mass of water, a mechanical, thermal, chemical and biological machine: a formidable object of study for scientists of all disciplines. But today, the Ocean machine is seizing up. The pressures weighing on the health of the Ocean are multiple. For example, we see increasing temperatures and acidification, which create a domino effect on marine life, and amplify floods and tropical cyclones. These problems are added to other perils such as pollution and the exponential growth of uses. Ocean-dependent communities, particularly vulnerable communities in developing countries, are under threat. Yet the Ocean stands as a powerful bulwark against climate change, thanks to its considerable capacity to store heat and carbon. Nevertheless, the vision of an infinite and indestructible Ocean is vastly outdated.

Protecting the Ocean so that it continues to protect us, covering all its extent from the coast to the deep sea, requires a multidisciplinary approach and appropriate governance. Navigating the Future VI, with its four outward-facing chapters linking to topics that any audience can identify with (People, Climate, Fresh Water, and Biodiversity), takes the next step towards these challenges and considers the role of the Ocean and marine science in the wider Earth system. Navigating the Future VI proposes what marine (natural and social) science research we need to help us address the challenges facing the planet, and with whom we need to collaborate to find solutions. Its chapters highlight how important the Ocean is in solving the climate change, biodiversity, and human crises we have created. For this, I would particularly like to thank the chapter (co)leads for taking on those roles: Francesco Marcello Falcieri, Juliette Aminian Biquet, Katrin Schroeder, Peter Kraal, Tainá Fonseca, and Carlos Pereira Dopazo. I would also like to thank the members of the European Marine Board Secretariat for their work in preparing this report.

Gilles Lericolais
Chair of Navigating the Future VI Working Group and Former Chair of EMB (Spring 2019 - Spring 2024)

October 2024

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Executive summary

The Navigating the Future publication series produced by the European Marine Board provides foresight on priorities for marine science and policy. Each edition builds on the messages of previous publications, taking the next steps in helping us to understand and manage the Ocean, learn how to use its resources sustainably, and keep benefiting from the services it provides.

Navigating the Future VI complements previous editions of Navigating the Future by considering the role of the Ocean in the wider Earth system, in relation to people (Chapter 2), climate (Chapter 3), fresh water (Chapter 4) and biodiversity (Chapter 5). Chapter 2 on the Ocean and People explores the different types of connections that exist between people and the Ocean, and how we need to reconsider these interactions to move towards sustainability and equity. Chapter 3 on the Ocean and Climate discusses both how the Ocean is being affected by climate change and its role in helping to address it. Chapter 4 on the Ocean and Fresh Water presents the complex interfaces between salt water, fresh water, and ice, as well as the Ocean and land, to demonstrate how challenges in one area also affect others, meaning they must be addressed together. Chapter 5 on the Ocean and Biodiversity highlights the critical role of biodiversity in the provision of ecosystem services to humans, and hence the need to take steps to further protect it. The document closes by considering how marine science itself should evolve and highlights how overarching aspects such as understanding and managing Ocean stressors, considering our Ocean governance structures, and exploring Ocean finance are vital to help us protect our Ocean (Chapter 6).

Contribution to the EU Mission: Restore our Ocean and Waters

This Position Paper and its recommendations support the direct objectives of the EU Mission: Restore our Ocean and Waters (Mission Ocean) in the following ways:

- **'Protect and restore marine and freshwater ecosystems and biodiversity'** by presenting the challenges facing marine ecosystems and recommending marine science research and policies to address these in the 'Ocean and Biodiversity' Chapter.
- **'Prevent and eliminate pollution of our Ocean, seas and waters'** by discussing the different sources and pathways of known and emerging marine pollutants and proposing marine science research and policy recommendations to address these in the 'Ocean and Fresh Water' Chapter.

In addition, the chapters on Ocean and People and Ocean and Climate include information and recommendations which will be critical to making the Mission Ocean a success. Without the contribution of people and their understanding of the importance of the Ocean for their health and to mitigate climate change, the Mission will not succeed.

EMB acknowledges that while the Working Group members who contributed to the document and its recommendations represent different European geographical location (see Annex 1), professional backgrounds, and career levels, their views do not represent all forms of diversity. This document has a European focus, but its messages and recommendations are relevant to stakeholders globally.

2021 United Nations Decade
2030 of Ocean Science
for Sustainable Development

Contribution to the UN Ocean Decade Challenges and Outcomes

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

- **'A clean Ocean'** (O1) where sources of pollution are identified, reduced and removed as well as **'Understand and beat marine pollution'** (C1) by discussing the different sources and pathways of known and emerging marine pollutants and proposing marine science research and policy recommendations to address these in the 'Ocean and Fresh Water' Chapter.
- **'A healthy and resilient Ocean'** (O2) where marine ecosystems are understood, protected, restored and managed, and **'Protect and restore ecosystems and biodiversity'** (C2) by presenting the challenges facing marine ecosystems and proposing marine science research and policy recommendations to address these in the 'Ocean and Biodiversity' Chapter.
- **'A productive Ocean'** supporting sustainable food and a sustainable Ocean economy (O3), **'Sustainably feed the global population'** (C3) by discussing factors that can influence the supply, location and quality of marine species used for food products in the 'Ocean and Biodiversity' and 'Ocean and Fresh Water' Chapters, and proposing recommendations that will improve the management of food provision in response to these factors in the future.
- **'An equitable Ocean'** (C4) for developing a sustainable and equitable Ocean economy by stressing the importance of recognising the many values of the Ocean and highlighting management, decision and governance approaches which are more likely to yield sustainable, and particularly equitable, outcomes in the 'Ocean and People' and closing Chapters.
- **'A predicted Ocean'** where society understands and can respond to changing Ocean conditions (O4) and **'Unlock Ocean-based solutions to climate change'** (C5) by outlining the likely impacts of climate change on the Ocean, and hence society, under different scenarios and highlighting how the Ocean could help mitigate these if properly managed in the 'Ocean and Climate' Chapter.
- **'A safe Ocean'** where life and livelihoods are protected from Ocean-related hazards (O5) and **'Increase community resilience to Ocean hazards'** (C6) by highlighting the potential human health and societal impacts from hazards related to climate change in the 'Ocean and Climate' Chapter, and polluted waters in the 'Ocean and Fresh Water' Chapter, and how those could be better understood, and eventually mitigated.
- **'An accessible Ocean'** with open and equitable access to data, information and technology and innovation (O6) and **'Expand the Global Ocean Observing System'** (C7) by making recommendations for the improvement of Ocean observing in the Introduction and highlighting additional observing needs to better understand the links between the Ocean and People, Climate, Fresh Water and Biodiversity in the respective Chapters.
- **'An inspiring and engaging Ocean'** where society understands and values the Ocean in relation to human wellbeing and sustainable development (O7) and **'Change humanity's relationship with the Ocean'** (C10) by challenging the 'accepted' ways in which people engage with and manage Ocean resources and proposing alternative approaches in the 'Ocean and People' Chapter.

Main recommendations by chapter

Ocean & People

Working together to manage our Ocean interactions

Strengthen future trajectory prediction capacity of the Blue Economy to inform policy

Estimate how, where, when, and by whom Ocean values are used to build a model of human-Ocean interactions

Reform Ocean governance to ensure equitable community participation and consideration of values and knowledge

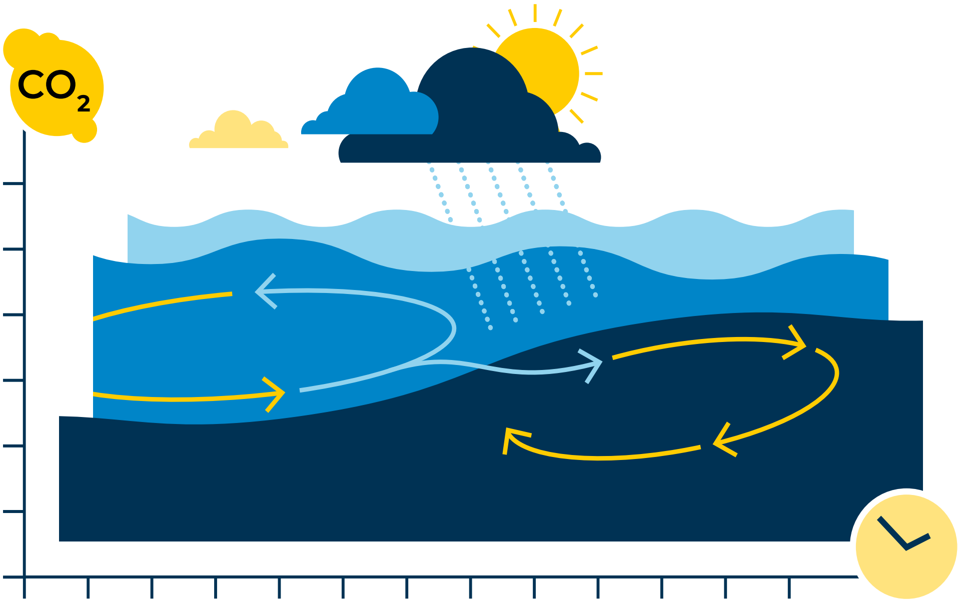
Recognise the need for structural change in Ocean policy and management

Use appropriate criteria to monitor engagement in citizen science projects

Increase capacity in and appreciation of all forms of collaboration

Ocean & Climate

An Ocean that is no longer impacted by climate change



Gain full understanding of marine ice sheet instability and impacts of melting

Build holistic coastal management plans to ensure adaptation and liveability

Address knowledge gaps highlighted by IPCC as ‘low’ or ‘very low’ confidence

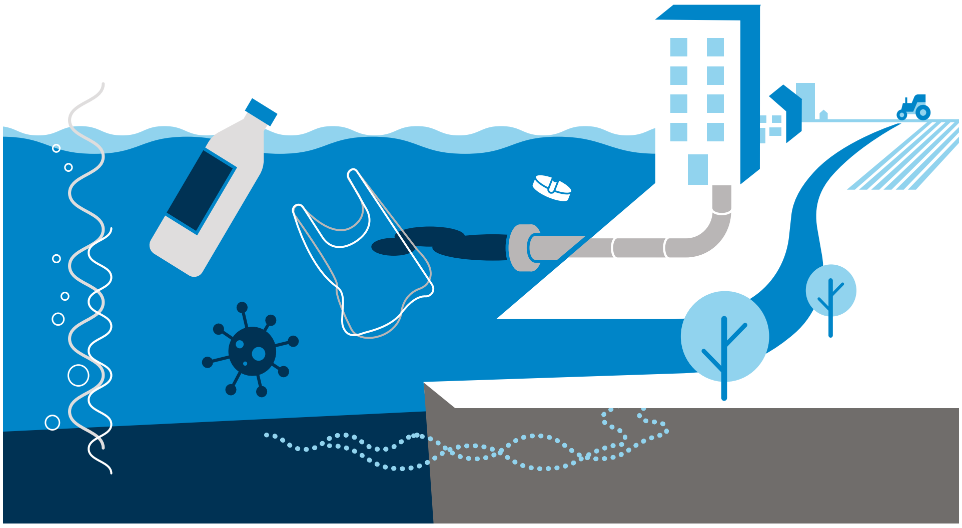
Conduct research to identify Ocean signals for coastal adaptation tipping points

Measure and map naturally occurring CO_2 and methane to address uncertainties related to potential release

Research the ‘triple threat’ synergistic effects of warming, deoxygenation and acidification

Ocean & Fresh Water

Clean and safe waters available to all communities



Include all contaminants and discharge pathways in risk assessments and EU Directives

Monitor deteriorating coastal freshwater reserves and submarine discharges

Broaden monitored parameters to understand salination impacts

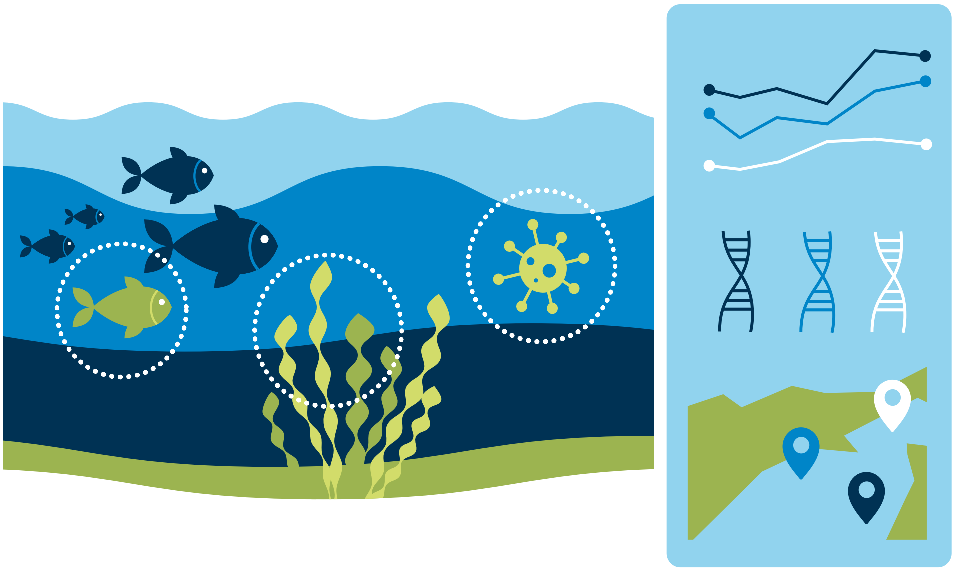
Create nature-based cost-effective technologies for emerging and legacy pollutants

Monitor biochemical and genetic markers to prevent the spread of diseases

Harmonise monitoring and reporting methods between freshwater and marine systems

Ocean & Biodiversity

A biodiverse Ocean that continues to provide ecosystem services



Study and effectively manage the impacts of emerging and expanding human activities on marine biodiversity

Assess the impact of human activities on ecosystems using cost-benefit analysis of their conservation or restoration

Study and monitor the spatial-temporal distribution and adaptive potential of marine organisms

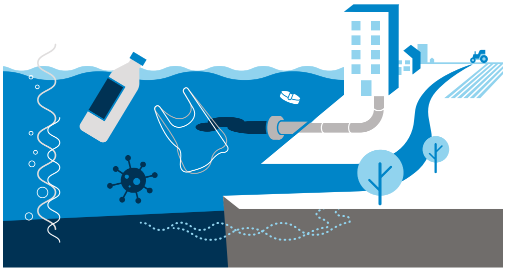
Evaluate the epidemiological, genetic, and ecological consequences of invasive species

Study the distribution of marine microorganisms to predict future epidemic risks from invasive microbes or resistance to antibiotics

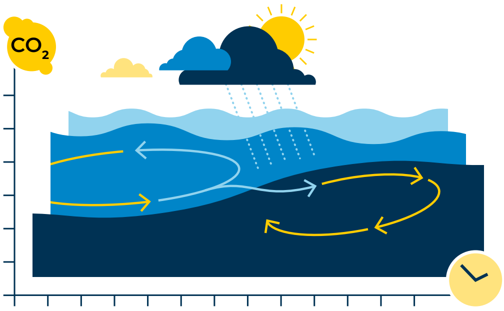
Promote all initiatives to increase biodiversity knowledge and capacity building, including the European Digital Twin, citizen science, recovering lost knowledge, and using traditional and new tools

Main cross-cutting requirements

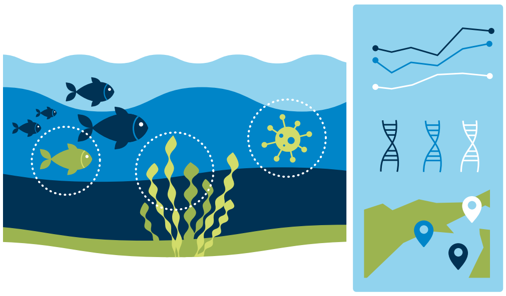
Working together to manage
our Ocean interactions



Clean and safe waters available
to all communities

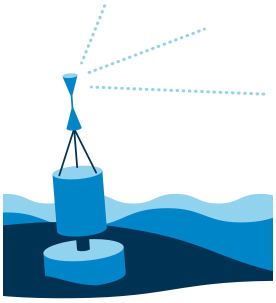


An Ocean that is no longer impacted
by climate change



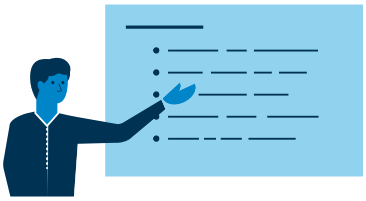
A biodiverse Ocean that continues
to provide ecosystem services

Requirements



- Sustained Ocean observations
- Balance between needs and resources

- Accessible data
- Input for the Digital Twin of the Ocean



- People trained to collaborate
- Research on impact of multiple stressors

- Sustained, long-term research funding
- Substantial, sustainable Ocean finance

- Harmonised Ocean-coastal-land management approaches
- Sustainable and equitable marine science

1

Introduction

Credit: Clément Proust, Pexels

To understand the vision of the main chapters of this document, we present the context within which they should be understood. We outline where Navigating the Future VI comes from, and what the publication and the broader Navigating the Future series aim to achieve. We continue by discussing the complex and evolving Ocean landscape which it aims to influence, and present overarching enablers which relate to all four chapters, before addressing the proposed next steps.

1.1 The Navigating the Future series

The Navigating the Future foresight series[1] provides the marine research community with periodic opportunities to step back from their core research and consider the overarching direction of marine science. Where is marine science heading and what are the key emerging topics, approaches and challenges? Where should upcoming research funding programmes and policies focus? It is therefore useful to look back at previous editions and see if the recommendations have been achieved, or if there have been any changes in policy direction since their publication.

Navigating the Future I, published in 2001 (ESF Marine Board, 2001) focused on the importance of a *marine* European Research Area (ERA) at a time where the European Commission's 6th Framework Programme (FP6)[2] was being developed and where no marine ERA yet existed. Published in 2003, Navigating the Future II (ESF Marine Board, 2003) further developed these ideas, discussing how marine science could be better integrated in Europe. Twenty years later, sea basin-, European- and even international-level collaborations lie at the heart of both marine science research and marine policy. Navigating the Future II called on Europe to *'move towards sound and true governance of its oceans and seas, integrating all components for a comprehensive and responsible management of its marine assets'*. After the publication of these documents, the Integrated Maritime Policy was released in 2007[3], with the specific inclusion of sea basin strategies. The European Commission also funded MarinERA[4] (2004-2009), a FP6 project that facilitated cooperation between National Marine Research Programmes in Europe, and in the European Commission's 7th Framework Programme (FP7[5]), the follow-up project SEAS-ERA[6] (2010-2014) was funded. These research area programmes evolved into the Atlantic programme AORA[7] followed by the All-Atlantic AAORIA[8], Blue-Med[9] in the Mediterranean Sea, BANOS[10] in the Baltic and North Seas, and Black Sea Connect[11] as instruments to increase marine research cooperation within the European sea basins.

In the build-up to FP7, Navigating the Future III (Marine Board - ESF, 2006) described marine science research in more detail, identifying major trends, opportunities, and future challenges, including climate change and the Ocean, marine biodiversity, coastal ecosystems, and the ecosystem approach to resource management. These topics were rooted firmly in natural sciences and did not include social science. We can see the parallels with key research trends that remain important today, including in the chapters of this present edition of Navigating the Future.

Navigating the Future IV (European Marine Board, 2013) reflected the increased focus on grand challenges in scientific research in the run-up to the Horizon 2020 Framework Programme[12]. It focused on how to address societal challenges (e.g. harvesting food and raw materials sustainably from the Ocean or producing energy) and research enablers (e.g. Ocean observing, marine training) linked to the Ocean. All the challenges and enablers identified then still stand today and have become even more relevant. Navigating the Future IV highlighted the continued need for a better understanding of the regional context of marine research. It also called for a forum of marine scientists, policymakers, representatives from industry, and coastal stakeholders that could convene regularly to ensure effective communication and synergies between sectors. This is now becoming a reality with the European Blue Forum[13], which was initiated by the European Commission in 2023, and the Sustainable Blue Economy Partnership[14] which also started in 2023.

Navigating the Future V (European Marine Board, 2019) built on these ideas and considered a longer timeframe, identifying the topics that would significantly advance our understanding of the Ocean to 2030 and beyond. It was released as discussions for the EU Framework Programme Horizon Europe[15] were underway, and for the first time highlighted the concept of sustainability science, bringing in the marine social science perspectives that had thus far

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[1] https://www.marineboard.eu/navigating-future
[2] https://eur-lex.europa.eu/EN/legal-content/summary/6th-framework-programme-2002-2006.html
[3] https://research-and-innovation.ec.europa.eu/research-area/environment/oceans-and-seas/integrated-maritime-policy_en
[4] https://cordis.europa.eu/project/id/515871
[5] https://eur-lex.europa.eu/EN/legal-content/summary/seventh-framework-programme-2007-to-2013.html
[6] https://seas-era.eu/
[7] http://www.atlanticresource.org/
[8] https://allatlanticocean.org/
[9] https://www.bluemed-initiative.eu/
[10] https://www.banoscsa.org/
[11] http://connect2blacksea.org/
[12] https://eur-lex.europa.eu/EN/legal-content/glossary/horizon-2020.html
[13] https://maritime-spatial-planning.ec.europa.eu/european-blue-forum
[14] https://bluepartnership.eu/
[15] https://eur-lex.europa.eu/EN/legal-content/glossary/horizon-europe.html

been missing from the series. Navigating the Future V highlighted the importance of the four-dimensional Ocean considered over volume and time, the impact of pollution and multiple stressors, and the need for a virtual platform of the Ocean supported by observations and models. This platform concept is being reflected in the Digital Twin of the Ocean that is a key target of the EU Mission: Restore out Ocean and Waters[16] (Mission Ocean), and of the UN Decade of Ocean Science for Sustainable Development[17] (Ocean Decade). The social science dimensions are also reflected in the newest funded Horizon Europe Mission projects to include socio-economic modelling into the Digital Twin of the Ocean.

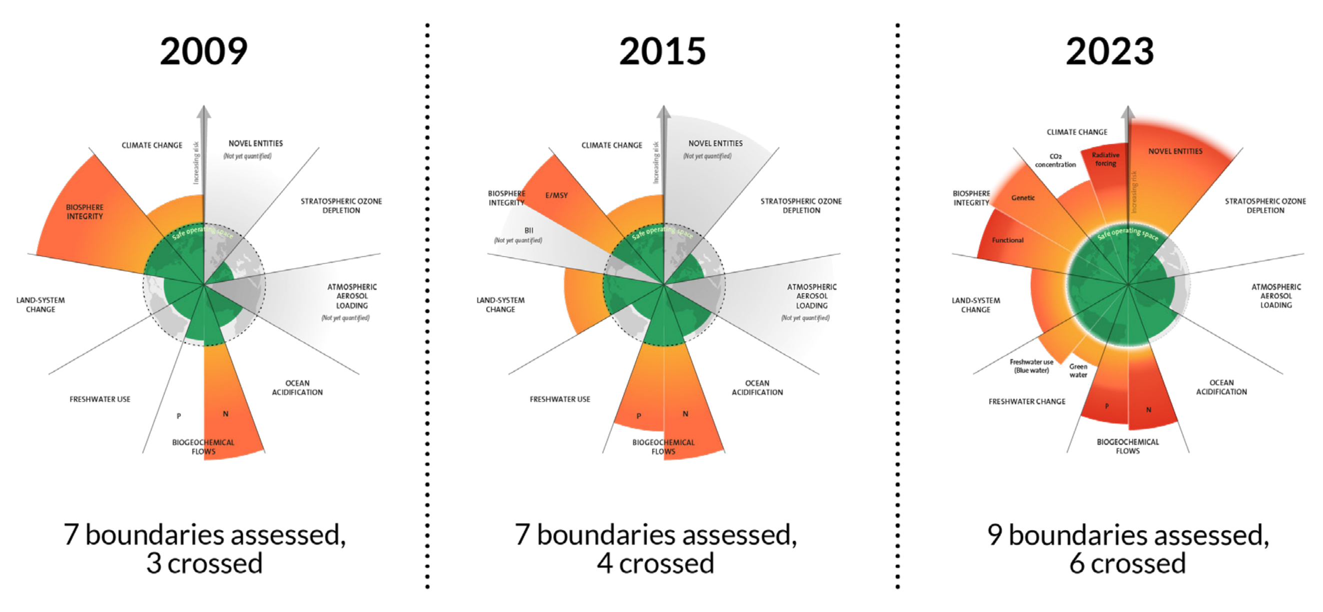
Released at the midpoints of Horizon Europe, the Mission Ocean and the Ocean Decade, Navigating the Future VI takes the next step and considers the role of the Ocean and marine science in the wider Earth system: i.e. the interaction between the physical, chemical, and biological processes on Earth. What natural and social marine science do we need to help us address the challenges facing the planet, and with whom do we need to collaborate to co-construct solutions?

While the early editions of the Navigating the Future series were pioneering publications that provided overarching European-level direction for marine science at a time when research priority setting was still focused at national or institute level, the current landscape is very different. Large-scale and ambitious initiatives such as the Ocean Decade, Horizon Europe and the Mission Ocean are providing clear visions for the future of marine science. Navigating the Future VI strongly supports and aligns with these visions, but also seeks to reach beyond the Ocean sphere to ensure that policymakers and the wider public understand the importance of the Ocean in helping to address the climate and biodiversity crises, for the provision of fresh water, and for the health and wellbeing of humanity.

1.2 Planetary boundaries

In the last century, technological advancements have gradually shaped the way humans interact with nature. Global quality of life has largely improved, with notable exceptions (e.g. current war zones), and with it, consumption patterns have increased. Increasing human populations and activities require large amounts of natural and synthetic resources, whose extraction and processing interfere with the balance of nature.

Discussions about concepts such as planetary boundaries and ensuring an ongoing and safe operating space for humans (Rockström *et al.,* 2009) have left the confines of academia and are now firmly embedded in political and societal discourse, although the political situation in Europe makes this enlightenment a fragile reality. This is particularly relevant since we have already crossed six out of nine planetary boundaries (Figure 1.1), and we urgently need to understand the consequences of humanity living outside its safe operating space (Richardson *et al.,* 2023). Of particular relevance to the Ocean are the boundaries of climate change and biosphere integrity, which were already crossed in 2009, and Ocean acidification, which although not yet crossed, is of significant concern, as discussed in Chapter 3.



Credit: Azote for Stockholm Resilience Centre, Stockholm University. Based on (Rockström *et al.,* 2009; Steffen et al., 2015; Richardson *et al.,* 2023), CC-BY-NC-ND 3.0

Figure 1.1 The evolution of the planetary boundaries' framework. By 2009 humanity had crossed three of these boundaries (biosphere integrity, climate change and biogeochemical flows); by 2015 we had also crossed land-system change; and by 2023 the boundaries of novel entities introduced by humans (e.g. chemical compounds) and freshwater change were also crossed.

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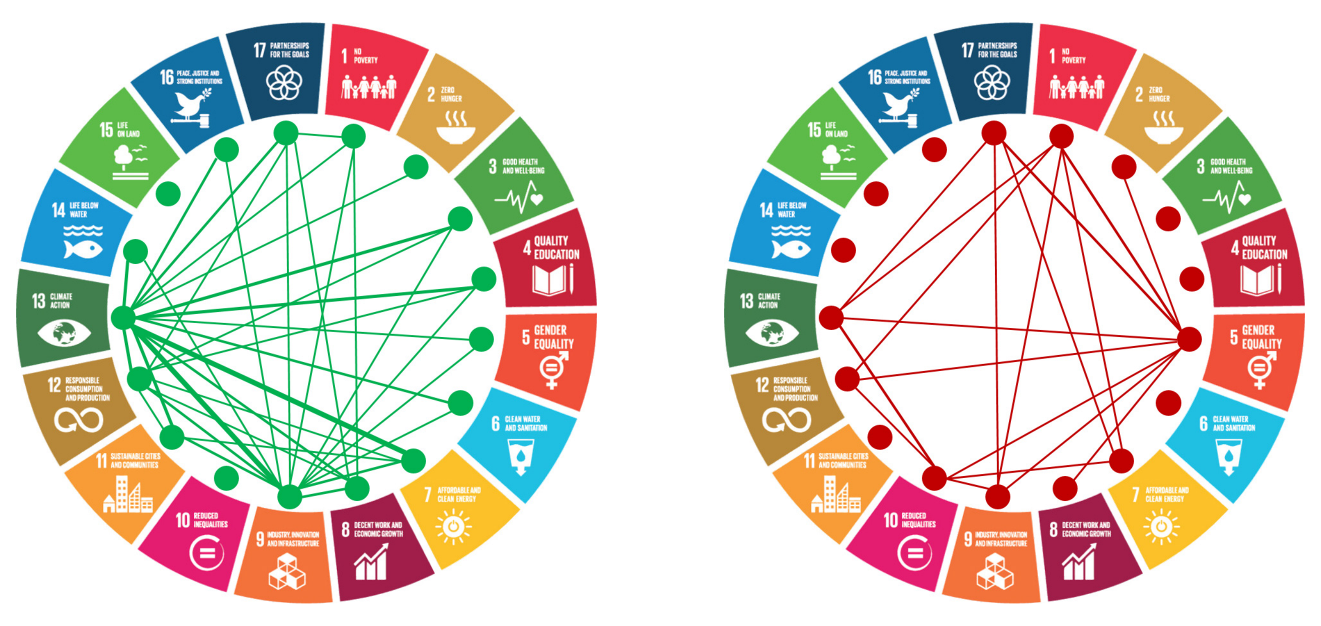
[16] https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/restore-our-ocean-and-waters_en

[17] https://oceandecade.org

1.3 Moving towards a sustainable Ocean future

Questions about the capacity of our planet to sustain our current way of life have shaped the governance landscape over the past 20 years. Similarly, questions about the ability of our Ocean to support life on Earth have also been growing within these discussions.

Internationally, the Sustainable Development Goals[18] (SDGs) outlined in the UN 2030 Agenda for Sustainable Development[19] published in 2015 provide an interconnected framework for working towards a sustainable future, balancing economic, societal, and environmental factors (see Figure 1.2), with SDG 14 and its targets dedicated to the Ocean, or protecting Life Below Water. SDG 14 has only positive synergies with other SDGs and raises no trade-off, indicating that protecting the Ocean and its inhabitants also has positive outcomes for society and the economy. As presented in Chapter 2, it is important that we consider these aspects together.



Source: Eurostat

Figure 1.2 Network images showing on the left, positive synergies between the SDGs, and on the right, trade-offs between them.

The UN 2030 Agenda sits alongside a myriad of other international-level governance initiatives on different topics (e.g. biodiversity, climate change) and sectors (e.g. shipping, fisheries) but for the Ocean, the broad aim of moving towards a more sustainable and healthy future remains the same.

In Europe, EU Member States must fulfil obligations associated with a series of Directives which aim to ensure that the Ocean and aquatic environments are managed sustainably, pollution is reduced, and ecosystems are protected and restored. For example, the Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC, 2008) came into being as political awareness of the importance of protecting the Ocean was growing. The MSFD dovetails with the Water Framework Directive (WFD, Directive 2000/60/EC, 2000), which highlights the importance of freshwater status, and the Urban Waste Water Treatment Directive (UWWTD, Directive 91/271/EEC, 1991), which aims to ensure that pollution is kept out of our freshwater systems. In addition, the success of the WFD and MSFD is dependent on the Common Agricultural Policy (Regulation 2021/2115, 2021), and the Nitrates Directives (Directive 91/676/EEC, 1991) as these instruments will enable a reduction of nutrients entering rivers and ultimately the Ocean. As discussed in Chapter 4, these obligations are critical for protecting the health of the Ocean and of people.

The recent drive to *'build back better'* following the COVID-19 pandemic, coupled with the decarbonisation ambitions of the EU Green Deal[20] and its related initiatives, are encouraging and stimulate sustainability, equality and environmentally aware development, and if properly implemented should support a more sustainable Ocean future. As discussed in Chapter 3, decarbonisation lies at the heart of our fight against climate change and ensuring that the Ocean can continue to play its role in this fight.

The EU is also taking significant steps to address the biodiversity crisis through the Nature Restoration Law (Regulation 2024/1991, 2024), adopted on 17 June 2024. If properly implemented, the Law would help to protect and restore Ocean biodiversity and address some of the challenges outlined in Chapter 5.

However, political compromises and decision-making, e.g. with geopolitical concerns, and the rise of nationalism in Europe, sometimes detract attention and funding from nature and Ocean protection initiatives such as those presented above, at least in

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[18] https://sdgs.un.org/goals

[19] https://sdgs.un.org/2030agenda

[20] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

the long-term. Questions of fair implementation (e.g. the farmer protests of 2024) can also lead to the retraction of previous commitments and dilute ambitions. Thus, to ensure a sustainable, well managed Ocean, we also need to ensure that citizens understand the wider role that nature and the Ocean play in their lives, and the implications of ignoring the planetary boundaries.

1.4 Eyes on the water

Understanding the Ocean is fundamental. If we do not observe it at multiple spatial and temporal scales, we cannot comprehend how it functions. If we cannot comprehend it, we will be unable to predict future scenarios, and adapt to or mitigate the impacts of Ocean health and stability degradation on society.

While the overarching aims of the various initiatives discussed above all align on the need to protect Ocean ecosystems and processes, implementation varies e.g. between countries, agencies etc. There is a lack of harmonisation in the methods used for data collection, monitoring and reporting, indicators, scales of assessment, quality assurance and control, and interpretation of results, leading to inefficiencies in data (re)use for reporting by Member States. Furthermore, the Ocean does not operate in isolation, but instead is fully integrated into other Earth systems. Thus, methods for regulation and management of the Ocean should align with freshwater, terrestrial, atmospheric and sectoral regulatory systems. At present, this is rarely the case and should be urgently addressed.

Nevertheless, the increasing availability of environmental and marine ecosystem data, new probes and sensors, computational power, and information and communication technologies are paving the way for unprecedented collection and integration of data and information. Advances include:

- An increase in the number and variety of Ocean observing systems, including profiling floats, autonomous and remotely operated underwater vehicles (AUVs and ROVs), and other Ocean observing systems (e.g. ARGO floats[21]), which continuously monitor Ocean parameters;
- New communication technologies that enable the retrieval of data from underwater sensors (e.g. acoustic modems, high-bandwidth communications);
- The development of microelectronics and mechanical designs that allow for example the measurement of physical and chemical properties using *in situ* optical sensors, and water sample analysis of environmental DNA (eDNA, see Chapter 5);
- The use of satellite remote sensing, unmanned aerial vehicle (drone) imagery, and underwater imagery, including high resolution photogrammetry for benthic habitats (Fraschetti *et al.,* 2024);
- The development and application of marine ecosystem models that enhance our understanding of ecosystem functioning, and improve our predictive capabilities for short-term forecasts, long-term climate projections, and assessment of the most likely consequences of management scenarios (Heymans *et al.,* 2018), as well as the additional links to socio-economic models to address human drivers of Ocean change;
- Advanced data processing and visualisation capabilities using artificial intelligence, which is rapidly revolutionising our ability to extract information and derive knowledge from Ocean data, allowing patterns and trends to be identified more efficiently (Guidi *et al.,* 2020); and
- New levels of global cross-sectoral cooperation such as in high-resolution Ocean floor mapping under the Seabed 2030 initiative[22].

However, these advancements also pose technical and non-technical challenges. Sensor power availability, navigation, and communication are all persistent technical issues. Maintaining crucial long-term observation systems, instruments, and remote Ocean infrastructure continues to be expensive, making their application and the long-term funding for these systems challenging (European Marine Board, 2021). However, it is notable that the few studies analysing the cost-benefit of Ocean observing indicate that investing in Ocean observing (e.g. Jolly *et al.,* 2021) and open marine data more generally (Jolliffe & Aben Athar, 2024) have a societal benefit. Non-technical challenges include lack of human capacity to deploy these new techniques and technologies, both in Europe and globally, which will become a bottleneck and a source of research output disparity if not addressed soon.

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[21] https://argo.ucsd.edu/

[22] https://seabed2030.org/

Figure 1.3 *In situ* Ocean Observation - Ocean Observing Systems and Sensors. This image was produced by and for the NeXOS project, funded under FP7.

Credit: Glynn Gorick, Eric Delory, Jay Pearlman, NeXOS project. CC-BY-SA 4.0

This vast array of Ocean data needs to be transformed into clear and organised information. At present, different sectors collect data for different purposes, with limited overarching strategy or overview. It is therefore critical that FAIR (Findability, Accessibility, Interoperability, Reusability) principles[23] for Ocean data are followed and data are digitised and made publicly available, so that they can be measured once and used many times. Numerous examples of open data resources already exist in the marine sphere (e.g. EMODnet[24], Copernicus Marine Service[25]), with the newest addition of the European Digital Twin of the Ocean[26] (DTO) enabling the integration of these data services with an easy to integrate infrastructure and the ability to bolt on bespoke models. However, given the need for information exchange across disciplines to address the cross-cutting challenges humanity faces, it is vital that all scientists seeking information are aware of these Ocean data resources and harmonisation principles. Public awareness of the available information is important, but the public may not be interested in the raw data, so data analysis and appropriate presentation are also important steps. Thus, the European DTO should be harnessed to create a citizen portal where the data available in a specific area can be used to describe the reality in the water beyond the waves - as we had already highlighted in the Epilogue of Navigating the Future V.

The Ocean remains under-sampled, and most data are inevitably biased in spatial coverage (e.g. more data from coastal waters versus deep sea, and from the Ocean surface versus seabed), seasonal coverage (e.g. more data from warm versus cold seasons), geographical locations (e.g. more data from regions with the capability to do more measurements) and data type (e.g. more physical versus biological data). Artificial intelligence, data-driven and process-based models need to be extended, refined, and integrated to provide increased reliability in:

- Interpolation (i.e. the estimation of unknown values within a range of known data) of experimental observations in space and time;
- Extrapolation (i.e. the estimation of unknown values beyond the range of known data points) of missing observations;
- Detection and early-warning of anomalies;
- Short- and long-term prediction of expected system behaviour; and
- Scenario analysis of the expected response of an ecosystem to the implementation of management policies (management strategy evaluation).

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[23] https://www.go-fair.org/fair-principles/

[24] https://emodnet.ec.europa.eu/en

[25] https://marine.copernicus.eu/

[26] https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/restore-our-ocean-and-waters/european-digital-twin-ocean-european-dto_en

The development of systems to understand the Ocean, including Digital Twins of the Ocean, is a challenge that requires the integration of knowledge from different scientific disciplines and key enabling technologies. These systems need to integrate: i) quality certified and harmonised FAIR data, ii) models, data analysis, and visualisation tools, including for virtual augmented reality, and iii) user-friendly graphical interfaces for information access and decision support. The DTO platform is a good start to this requirement that needs to be followed up with good graphic interfaces and decision support tools.

To fully develop the information systems such as DTO we require:

- The identification of monitoring priorities, harmonisation, intercalibration and integration of real-time and near real-time observing capabilities and data streams;
- Strengthening and expansion of existing observing capabilities to meet all the priorities;
- Development, deployment and testing of novel technologies (e.g. new sensors, drones and other autonomous vehicles, genomic observations, Internet of Things (IoT) and Internet of Underwater Things (IUT));
- Artificial intelligence and interpolation techniques to reduce uncertainty and support efficient numerical simulation; and
- Outreach and dissemination of observations and model-based assessments.

These needs are particularly pertinent given that people from many different backgrounds will need to access, use, and understand Ocean data, and use it to make informed decisions. Artificial intelligence systems may also help to reduce human biases and inconsistencies in data analysis, but only if properly developed, as inappropriate development can perpetuate those biases.

1.5 Where next?

The Ocean as both a solution to and a casualty of the impacts of anthropogenic stressors has never been so apparent. The need to strengthen the understanding of the Ocean, and action towards its improved health, was first officially recognised at global level within the context of climate change under the UN Framework Convention on Climate Change (UNFCCC) by governments at the 25th Conference of the Parties (COP) in 2019[27]. In addition, several high-level conferences, such as the Our Ocean and UN Ocean Conference series, and the 2022 One Ocean Summit, have helped to bring the Ocean firmly into mainstream political discussions. Topics such as plastic pollution, biodiversity loss, overfishing, deep-sea mining, marine heatwaves and the UN Biodiversity Beyond National Jurisdiction Treaty[28] have also helped to bring the Ocean to the attention of the public and policymakers. It is therefore timely to capitalise on the interest and concern already generated. The global marine research community can take a visible and active role in furthering these discussions, highlighting Ocean challenges, and proposing Ocean solutions, including ideas for implementing existing agreements and treaties. Navigating the Future VI, with its four outward-facing chapters linking to topics that a wide audience can identify with (people, fresh water, climate, and biodiversity), provides a means to do so. As highlighted in the 2023 Vigo Declaration[29], the European marine science community is working together towards solutions and the provision of transdisciplinary, science-based policy advice to all levels of governance.

Navigating the Future V recommended that the marine research community should seek to break out of its traditional silos to work together in a transdisciplinary manner across and beyond disciplines. Other initiatives highlighted in this introduction (e.g. Ocean Decade and Mission Ocean) also encourage researchers to work across e.g. topics and regions. The four chapters of Navigating the Future VI cover topics that cannot be addressed without doing so. This is by no means a straightforward undertaking. It requires reaching across interfaces and jargon, with all the challenges that arise from doing so. But we should not be discouraged. The significant interconnections between the four Navigating the Future VI chapters demonstrate that we are already working at the interface between topics. We use infrastructure, equipment and methods that cross national and regional interfaces, and we as marine researchers and as humans naturally sit on a land-sea interface. We can take heart from this, and from the significant progress we have already made since Navigating the Future I. Truly working across and beyond disciplines in our research is the next logical step for the marine research community. Navigating the Future VI will help us take that step.

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[27] https://unfccc.int/conference/un-climate-change-conference-december-2019

[28] https://documents-dds-ny.un.org/doc/UNDOC/LTD/N23/073/63/PDF/N2307363.pdf?OpenElement

[29] https://www.euroceanconferences.eu/vigo-declaration

2

Ocean and People

Credit: Fuka Jaz, Pexels

Marine sciences have shifted from studying natural systems individually, to considering their interconnections, including with human systems and their multiple dimensions, such as cultures, needs and values (Link *et al.,* 2017). The importance of the Ocean specifically for human health has been highlighted previously in EMB Position Paper N°. 19 on linking Ocean and human health (Moore *et al.,* 2013), and subsequently in the SOPHIE Project Strategic Research Agenda for Ocean and human health in Europe (H2020 SOPHIE Consortium, 2020), in EMB Policy Brief N°. 8 on the policy needs for Ocean and human health (European Marine Board, 2020) and most recently in a report commissioned by the High Level Panel for a Sustainable Blue Economy (Fleming *et al.,* 2024). However, the links between the Ocean and human societies and cultures have not been as well understood.

2.1 Exploring the dynamic relationship between humans and the Ocean

The dynamic relationship between humans and the Ocean has evolved over millennia, shaped by cultural, economic, and technological developments. In addition to its role as a place for spiritual activities, the Ocean has historically been perceived as a vast territory to be discovered and a source of resources to be exploited for economic gain and to sustain livelihoods. In an increasingly populated and industrialised world, many societies now believe that they exist separately from their natural environments, which has led to accelerated climate change, the loss of biodiversity and the degradation of marine habitats. We need to return to an understanding that humans are part of the marine ecosystem and implement these ideas in research and policy.

The concept of ecosystem services, which emerged in the 1970s, only reached the marine realm in the 2000s, when it marked a significant shift in thinking about the relationship between humans and nature. Later, the natural capital concept[30], among others, emphasised the economic and non-economic value of ecosystem services, such as their cultural, spiritual, and ecological significance, as well as the importance of maintaining the resilience of marine ecosystems for the benefit of human communities. As a result, ecosystem services are typically clustered into three broad categories: provisioning services (e.g. fishing and aquaculture); regulatory and maintenance services (e.g. climate change buffering and carbon sequestration); and cultural services (e.g. tourism and recreation) (Wallace, 2007).

These concepts have played a crucial role in promoting a more comprehensive understanding of the interdependence between humans and the natural world. However, they are all rooted in economic thinking, so they fail to capture the full range of values that need to be considered (Villasante *et al.,* 2023). In addition, recent social science concepts, such as marine and blue justice (Bercht *et al.,* 2021; Bennett *et al.,* 2023) are based on more relational approaches to nature (Nightingale *et al.,* 2019). These approaches try to overcome a conceptual divide between nature and humans, or nature and culture.

Credit: Leif Linding, Pixabay

Tourists at the beach

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[30] https://naturalcapitalforum.com/about/

2.1.1 The many values of nature

People experience the same marine environments in different ways because they have different world views, knowledge systems and personal values (Pascual *et al.,* 2023). Values related to the (marine) environment can be broadly classified as instrumental (nature as a resource), intrinsic (inherent worth of nature), and relational (nature as part of culture, social cohesion and identity, e.g. stewardship for a place) (Chan *et al.,* 2016). The values embraced by individuals and societies drive how they interact with the world and how they produce knowledge. While policies and research have mostly focused on instrumental values of nature, as illustrated by the literature on ecosystem services (Pendleton *et al.,* 2016), other values are also increasingly being considered, especially relational values and their links with human wellbeing, including in economic evaluations.

Linked to the values that different people have, different narratives or different ways of perceiving what sustainability means is key to many current maritime conflicts. These narratives (e.g. what are the different narratives, how can they impact on marine management decisions and interpretation) are still under-researched (Nightingale *et al.,* 2019). To foster this research the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Task Forces on Scenarios and Models developed the Nature Futures Framework to explore positive futures based on varying degrees of emphasis on intrinsic, relational and instrumental relational values (e.g. Pereira *et al.,* 2023). For example, a seawall built of cement that ultimately causes erosion but currently appears to provide protection in a given area may be perceived by some as sustainable, whereas other coastal protection measures, such as planting vegetation to help stabilise sand dunes, may be interpreted as a more sustainable approaches by others. See EMB Position Paper N°. 27 on Coastal Resilience (Villasante *et al.,* 2023) and Chapter 3 for more discussion on adaptation measures for climate change.

Cultural values are very important drivers for the narratives that societies favour. Our European maritime cultural diversity is often intertwined with environmental values, such as fishing heritage, and is a key asset that needs to be protected in its own right (IPBES, 2022). It also means that a highly transformed landscape can still produce significant cultural ecosystem services (Cusens *et al.,* 2022). As we aim to standardise marine management objectives in a region with diverse maritime cultures, we must be aware that not all cultures understand and value the marine environment in a discrete, spatially fixed manner. This means that spatial planning alone, describing the marine environment as geographical delineations of human activities, does not capture the many ways in which the marine environment is perceived and experienced by coastal communities (e.g. in terms of culture, history, and physical and spiritual experiences).

To properly account for these diverse sets of values, valuation methods have had to evolve, as many of these methods relied on estimating the monetary value of nature. For example, cultural ecosystem services underpin marine tourism, the economically dominant sector of the Blue Economy, yet their value remains poorly integrated in ecosystem valuation exercises (Erskine *et al.,* 2021). IPBES (2022) introduced a methodological framework and guidance that accounts for the diversity of values related to nature (IPBES, 2022), which will help build a global consensus on how to account for nature's contributions to our societies. With this valuation framework in place, the challenge is to find ways for communities to demonstrate the existence of the natural 'capital' they benefit from and improve its recognition and consideration in decision-making.

2.1.2 Emergence and growing understanding of feedback between the Ocean and society

Science is key to understanding the feedback between human activities and the marine environment through various economic, social, and ecological pathways. Indeed, human activities such as fishing, shipping, and tourism can significantly impact marine ecosystems, including changes in biodiversity and ecosystem status. Human activities can also change the physical characteristics of the Ocean (Nash *et al.,* 2017). In turn, the state of the marine environment can affect human society by impacting the resources, such as fish populations, water quality, recreational amenities, coastal landscapes, and marine seascapes (H2020 SOPHIE Consortium, 2020). Some drastic human-induced ecosystem changes have already impacted human populations and their livelihoods (e.g. overexploitation-driven fish population collapses leading to changes in targeted fish species, or transitions to a growing service economy for coastal communities). Governance systems have yet to further adapt to these human and ecosystem changes across spatial and temporal scales (Van Assche *et al.,* 2020, see Section 2.4). Marine sciences study the feedback between changes in human activities and ecosystem Guidance from the scientific community is required on how to implement the necessary governance changes to be able to manage the multiple and interacting human pressures on the marine environment sustainably and holistically, as highlighted in EMB Position Paper N°. 27 on Coastal Resilience (Villasante *et al.,* 2023).

2.1.3 The role of science in marine conflicts

Science, values, and consideration of Ocean-human relations have evolved in a sea of conflicts that have been a part of human history since ancient times. For example, disputes over fishing rights, offshore drilling rights and control of shipping lanes have fuelled conflicts such as the North Atlantic 'Cod Wars' between Iceland and the UK (Katz, 1973; Steinsson, 2016). National and international politics, including ongoing and future conflicts and wars, deeply affect research (Robinson, 2020), setting its priorities and resources, for example through funding. In turn, the role of science in understanding these conflicts and supporting fair Ocean governance has significantly changed over the last decades, as has the value given to marine scientific knowledge. To design relevant policies, we need to understand these conflicts and deploy mediation and science diplomacy to prevent escalation or additional conflict emerging from these policies or in science-policy interfaces (Mackelworth *et al.,* 2019).

Science diplomacy can have a role in post-war conflict resolution and in demonstrating support to involved parties, with benefits for scientific research and the environment, and can promote inclusivity, diversity, evidence-based decision-making and capacity building. As an example, in Ireland, the Peace programmes initiated in 1994[31] intended to support peace and reconciliation projects with Northern Ireland and the border counties. Created as a partnership between the European Commission and the governments of UK and Ireland, the programme continues in its latest iteration as the Peace Plus[32] programme, supporting peace and prosperity in Ireland. Themes identified for the post-conflict society include those linked to Biodiversity, Nature Recovery and Resilience, and Marine and Coastal Management and Water Quality[33]. Solidarity has also recently been demonstrated in December 2023 by the European Commission in the opening of a Horizon Europe office in Kyiv, Ukraine, and in launching a series of dedicated instruments[34] under Horizon Europe to support Ukrainian researchers and start-ups. However, science diplomacy remains a diplomatic tool that can also be used to assert political power (e.g. within the capacity of producing knowledge, which can lead to decisions) and national or international interests, for example over resources (Turnhout *et al.,* 2020).

Ocean science diplomacy, defined as the intersection of science with international Ocean affairs (Polejack, 2021), has become one of the tools to address maritime conflicts, by fostering collaboration between nations on specific topics (e.g. sharing knowledge on scientific methods). This fosters broad scale international cooperation, including the development of shared solutions, such as Marine Protected Areas and sustainable fishing.

Overall, science maintains a privileged place in policymaking, as demonstrated in the international discussions around the UN Biodiversity Beyond National Jurisdiction Treaty regarding Areas Beyond National Jurisdiction (ABNJ) (Schadeberg *et al.,* 2023). There has been a growing scientific focus on how policies and scholarship interact, questioning the portrayed image of objectivity. This has highlighted how the underlying assumptions of scientific knowledge production (e.g. favouring some actors and types of knowledges and expertise (Pérez-Hämmerle *et al.,* 2024)) and science policies (e.g. funding policies) are influenced by policy narratives, and consequently governance of marine spaces and people. As such, this is an area which deserves further attention if scientists are expected to work across disciplines and bring their expertise closer to decision-making.

2.2 Collaboration

In the early 21st century we face significant and/or unprecedented challenges, from pandemics, to wars, and the impacts of biodiversity loss and climate change. These challenges cannot be solved by single disciplines. In this context, navigating the complexities of human-Ocean relationships requires collaborative and integrative approaches. For example, issues such as shifts in species distributions, coastal erosion, sea-level rise or marine pollution all require collaborative approaches that include natural science, economic, political, and social approaches coupled with non-academic stakeholders, in order to understand the drivers and develop solutions. Collaborative working extends beyond academic disciplines and includes businesses, policy advisors, policymakers and politicians, NGOs, local and Indigenous leaders, and a range of other stakeholders.

It is also through collaborative work that one can learn to value the knowledge and practices of others. There is a growing recognition of different knowledge systems, from various expertise and communities. Indigenous peoples and local communities are key actors in marine areas and hold a wealth of knowledge and know-how but can also be particularly affected by climate change and biodiversity loss. While incomplete, the growing participation and recognition of these communities and other types of knowledge in science-policy interfaces show the benefits of including various perspectives for both science and policymaking, as illustrated by IPBES and the Global Biodiversity Framework (Fajardo *et al.,* 2021).

With the growing interest in interdisciplinarity, a multitude of terminologies has emerged. In Navigating the Future V (European Marine Board, 2019), definitions for some of these terms were given to underpin Chapter 6 on Sustainability Science, although it is noted that they differ slightly from what is presented below. Whilst there are no 'right' or 'wrong' definitions, it is important to have agreed definitions when collaborating. In this document, we use the following definitions[35] (Figure 2.1):

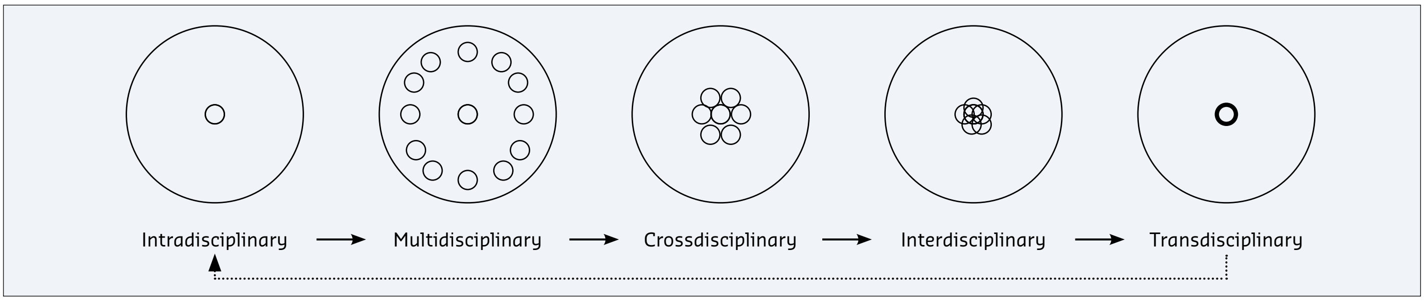

Figure 2.1 A spectrum of five forms of working across disciplines. Disciplines collaborating can fully integrate methods and knowledge of one another and be merged into one discipline, hence the dotted arrow back to an intradisciplinary approach. Taken from https://www.arj.no/2012/03/12/disciplinarities-2/

Credit: Alexander Refsum Jensenius, CC-BY-SA 4.0

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[31] https://www.seupb.eu/past-programmes/peace-platform

[32] https://www.seupb.eu/peaceplus

[33] https://static.gluons.ai/com_Qnwc2EZmEg/support/PEACEPLUS_Overview_24052023.pdf

[34] https://research-and-innovation.ec.europa.eu/strategy/strategy-2020-2024/europe-world/international-cooperation/association-horizon-europe/ukraine_en

[35] See examples for each definition at https://valuing-nature.net/sites/default/files/documents/demystifying/VNP25-DemystifyingInterdisciplinaryWorking-A4-28pp-144dpi.pdf and the EMB Science Webinar given by Nicola Beaumont on interdisciplinary work https://www.marineboard.eu/events/why-what-and-how-interdisciplinary-endeavour

Intradisciplinary working: Working within a single discipline either as an individual or a collaboration of people from the same discipline. A discipline is defined as a specific area of work.

Crossdisciplinary: Working in one discipline with awareness of one or more other disciplines but without in-depth communication or collaboration.

Multidisciplinary: Several individuals or groups from different disciplines working together, sharing their knowledge in a way which is additive rather than integrative.

Interdisciplinary: Deep integration of knowledge and/or methods from two or more disciplines, leading to the establishment of a new level of discourse and/or methodological approaches.

Transdisciplinary: Uniting of knowledge and methodologies beyond disciplinary perspectives, subordinating disciplines and resulting in an outcome which is not recognisable from the original parts.

The term ‘transdisciplinary’ is particularly controversial and *‘can be understood as knowledge production that either transcends different disciplines, or that transcends the disciplines to work with non-academics’* (Strand *et al.,* 2022). Whilst collaborations between academics and stakeholders are clearly crucial, these working relationships can be anywhere on the spectrum from cross- to transdisciplinary, and as such, using the term ‘transdisciplinary’ to define this working relationship seems unnecessarily restrictive. It is also key to note that there is no ideal place to work along this spectrum, and no one approach is ‘better’ than another: it depends on the context. There is value in using collaborative approaches from across the spectrum highlighted above, but there should be clear and active communication from the outset between all parties about where a project sits on this spectrum to avoid confusion, to ensure that the selected approach is appropriate for the questions being addressed, and to ensure the goals of the project are met. Integrating scientific and stakeholder knowledge is challenging but can follow the following seven guiding principles in achieving successful collaborations as proposed by Beaumont (2020):

- Respect for the other disciplines and activities;
- Take time to learn and understand the language and methods;
- Communicate in ways understandable for everyone;
- Embrace personalities to bring different people to work together;
- Prepare not to miss any unfamiliarity across disciplines that needs consideration;
- Adapt to unpredictability; and
- Share about your experiences at all stages of the project.

Most large projects now aspire to inter- and transdisciplinarity and many large funding programmes ask for it, including co-development with non-academic collaborators, for example Belmont Forum[36], Horizon Europe and Biodiversa+[37]. The review process for these funding streams needs to be updated to evaluate inter- and transdisciplinary projects, for example by ensuring a diverse review panel with relevant expertise in collaborative working and including clear assessment criteria for transdisciplinarity (see for example the Belmont Forum). Given the different interpretations of the terminology, it is also important that funding calls are explicit in what level of collaboration they expect when using a particular term. This could assist both in managing expectations and ensuring that the required level of collaboration is actually achieved in practice within the project.

Once funded, success criteria need to be assigned to evaluate the multidisciplinary approach used. At present, funded projects often revert to more siloed working practices once underway. This is exacerbated by the fact that developing meaningful inter- and transdisciplinary collaborations are very time consuming. Unfortunately, collaborations built on project funding are difficult to sustain post-funding and resources need to be constantly reinvested to maintain these collaborations. Therefore, inter- and transdisciplinary efforts should be institutionalised. This includes restructuring institutions around societal challenges rather than disciplines in a meaningful manner (beyond the creation of ‘centres’ which continue to depend financially on discipline-focused departments). Importantly, such changes are needed in knowledge creation institutions as well as policy delivering institutions. Seed funding could establish collaborations which can then be taken forward within normal project funding programmes. This could provide the time and opportunity for collaborative relationships to be established and may mean that the actual project work is also conducted more collaboratively.

There are also limited structures in place for career development in inter- and transdisciplinary research. Inter- and transdisciplinary researchers can struggle to succeed, as research institutes and promotion procedures tend to be organised by discipline and career evaluation criteria are driven by single discipline practices. Thus, although there is a clear need and aspiration for inter- and transdisciplinary approaches, the lack in organisational, institutional, and logistical structures result in a lack of capacity and very few successful applications. Examples of solutions could include the development of new metrics for success that take into account engagement in collaborative approaches, academic journals that focus on collaborative working, and/or better appreciation of collaborative outputs within existing journals. This would better reward inter- and transdisciplinary researchers within the current system of metrics based largely on publication.

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[36] https://www.belmontforum.org/

[37] https://www.biodiversa.eu/

2.3 Blue Economy and the Ocean's contribution to people

As a provider of energy, goods and services, and a vector for trade, the Ocean is an essential and growing component of global economic development (Jouffray *et al.*, 2020). In 2010, at the High-level Event on Biodiversity, Ban Ki-Moon, the UN Secretary-General at that time declared *"Maintaining and restoring our natural infrastructure can provide economic gains worth trillions of dollars each year. Allowing it to decline is like throwing money out of the window"*. Investments in the 'sustainable Blue Economy' (COM/2021/240 final, 2021) are expected to increase, driven by global population growth and its concentration in coastal areas, and by increased international wealth, particularly in emerging economies (OECD, 2016). Understanding the economic trajectories of these activities and how they can be governed is critical and should be addressed through understanding the underlying values and narratives of different groups of people, as well as the scientific methods and disciplines used (see Section 2.1.1). We approach this theme through an economic lens, and we consider the governance questions it raises in the next section.


Credit: EMB

Wind turbine installation vessel being loaded in Ostend, Belgium

The 'Blue Economy' is a controversial term (e.g. Voyer *et al.*, 2018) and despite its growing importance, there is currently no harmonised international definition of the Blue Economy (see for example the definitions from the Organisation for Economic Co-operation and Development (OECD), EU, System of Environmental Economic Accounting (SEEA)), and no unified statistical system to track its evolution. Nevertheless, a consensus is emerging that for economic monitoring purposes, the Blue Economy can be defined as all the economic activities connected to the Ocean and coasts (Thébaud, 2017). These activities rely on the extraction, processing, and use of maritime spaces or resources (living, energy or mineral), the exploitation of the physical properties of the sea and seabed, and the biophysical properties of marine and coastal sites. These Blue Economy activities include manufacturing and service sectors upstream of the industries that directly exploit the sea and the coast. The Blue Economy comprises established sectors such as maritime transport, shipbuilding, fishing and aquaculture, marine and coastal tourism, and oil and gas exploitation. It also includes highly technological sectors, such as undersea cables, or the construction of specialised ships. Furthermore, there are emerging sectors, such as the exploitation of offshore renewable energy, the exploitation of deep Ocean minerals, upscaling forms of aquaculture such as algal production, and the development of marine biotechnologies. To date, efforts to characterise the Blue Economy have been largely limited to evaluating the economic production and jobs created by maritime sectors, and by non-commercial public services such as defence, environmental protection and research (Kalaydjian & Adeline, 2022). In addition to the wealth and employment generated by these activities, we should also account for other values and ways of valuing nature, as highlighted in Section 2.1 and discussed below with respect to the importance of preserving ecosystem services. We need to gather data and better describe these values and their interaction with ecosystem dynamics, economy and policymaking processes to better estimate where, when and by whom these values are used. When integrated, this information can lead to a better understanding of the current human needs from and interactions with the Ocean.

Beyond the methods to assess the actual and potential importance of the Blue Economy that still need to be developed, there is growing recognition that we need to strengthen our capacity to predict future trajectories of the Blue Economy to inform sustainable development policies. These predictions are key not only to understand future social, ecological and economic landscapes in a status quo scenario, but also to predict manners by which we can adapt to local, regional, or global uncontrollable changes. This requires identifying the main economic, technological, social, cultural, institutional and environmental drivers to which maritime activities will respond, as well as the dynamics of these responses. We therefore need to develop methods that will allow us to understand how the Blue Economy could evolve, considering interacting sectors and multiple scales. We also need an understanding of the complex feedback loops between these drivers and their responses. This will require expanding the range of available methods and tools to analyse the future of the Blue Economy at multiple scales (e.g. Planque *et al.,* 2019), including how it will adapt (O'Donoghue *et al.,* 2022). Research should also address the implications of cross-sectoral interactions (Bellanger *et al.,* 2020), equity considerations (Cisneros-Montemayor *et al.,* 2021) and the role of social acceptability (Cavallo *et al.,* 2021). We may build on existing Ocean observing systems (e.g. GOOS, EOOS) to include spatially explicit information on human activities, and their economic and social dimensions, to improve our empirical understanding of spatio-temporal interactions between human activities and marine ecosystems, and their responses to multiple drivers.

2.3.1 Ocean's contribution to people

During the second half of the 20th century, we focused on the impact of resource extraction on the ability of ecosystems to continue providing these services (Millenium Ecosystem Assessment, 2005). Now, multiple stressors (see Section 5.3) such as Ocean warming, deoxygenation and acidification, overfishing, invasive species, eutrophication, and pollution are impacting and changing marine ecosystems, affecting the services they provide. The importance of valuing ecosystem services for sustainable development is now emphasised by many policy documents, such as the EU Blue Economy reports (European Commission, 2020, 2022), which were underpinned by the EMB Future Science Brief N°. 5 on Valuing Marine Ecosystem Services (Austen *et al.,* 2019). We highlight the most well-known cultural, provisioning, and regulating services of the Ocean below.

The resilience and maintenance of cultural services rests on maintaining biodiversity-rich ecosystems. It also relies on ensuring that communities using these cultural services can adapt to changing conditions (Villasante *et al.,* 2023). This includes maintaining resilient recreation and tourism activities that can extract cultural services from changing ecosystems while contributing to protecting or restoring them.

The provisioning services of the rich fisheries and aquaculture potential of the seas, if sustainably managed, can be a significant source of welfare for society and can support livelihoods and employment opportunities. The study of fish stock biology and stock assessments have dominated fisheries science, but a more comprehensive understanding of marine ecosystems, in which fish populations play a key role, and where interactions with other ecosystems components, fishing behaviour and other oceanic uses are considered, is needed to ensure effective ecosystem-based management of fisheries and of the social-ecological systems that face multiple stressors. This is now taken up by the main body that calculates the amount of fish that can be caught in the North Atlantic, the International Council for the Exploration of the Sea (ICES[38]), who have broadened their mandate to include food web interactions in their work (WKFOODWEB). The Renewable Energy Directive (Directive 2018/2001, 2018) and the European Green Deal (COM/2019/640 final, 2019) have also highlighted the role that the Ocean will need to play in providing space for renewable energy infrastructure development and energy generation.

Regulatory services provided by healthy marine ecosystems include the key role they play in carbon sequestration, but its continuation is very dependent on keeping greenhouse gas emissions in check as is highlighted in EMB Policy Brief N°. 11 on Blue Carbon (European Marine Board, 2023).

These examples demonstrate a need for a greater multi-scale, mechanistic understanding of how human activities are embedded in ecosystems to support ecosystem-based management. Given the rapid changes in human activities and climate, research into these processes must consider mitigation and adaptation scenarios regarding the impacts of climate change on marine social-ecological systems. One way to do this could be by using decision-making innovation laboratories[39] dedicated to Ocean policy to test the impacts of different strategies.

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[38] https://www.ices.dk/; https://www.ices.dk/community/groups/Pages/WKFoodWeb.aspx

[39] https://ideanote.io/blog/innovation-lab-know-everything

2.4 Understanding the governance of maritime activities

2.4.1 Governance of common-pool resources

A large fraction of the Blue Economy relies on the use and extraction of common pool resources for goods and services (Box 2.1), which are notoriously difficult to govern (Ostrom, 1990). However, the literature has largely focused on specific sectors, such as fisheries, and relatively local systems (Cox *et al.,* 2010). Blue Economy diversification is generating conflicts that require coordination across multiple policies and jurisdictions (Bellanger *et al.,* 2021). We need to understand how management systems can be sustained and adapted in the face of change (Young, 2010) and the ways in which issues of equity and justice can be addressed for these systems to be broadly supported (Bennett *et al.,* 2021).

BOX 2.1 COMMON-POOL RESOURCES

Common-pool resources are both non-exclusive in access (i.e. it is difficult, if not impossible, to exclude users from accessing the resource) and finite (e.g. when harvested, the resource is no longer available to other users). This creates what economists call externalities: the harvest by a user will have negative impacts (reduced harvest possibilities) for others, but if the user does not have to pay for these impacts, they will only consider their own costs and benefits. This leads to each user deploying excess harvesting capacity, therefore generating conflicts, and degrading the resources. Wild fish stocks, marine space, biodiversity, and mineral resources are good examples of common-pool resources.

Common-resources management involves the establishment of access regulations, i.e. individual or collective limitations on harvesting or access.

Marine Spatial Planning (MSP) and associated tools such as Marine Protected Areas (MPA) have become a favoured approach to address the complex challenge of managing human activities at sea across multiple objectives such as biodiversity, climate, energy and food production, and local employment (Chalastani *et al.,* 2021). While this approach has many benefits, it is not a panacea. MSP can worsen competition and conflicts between sectors (Lester *et al.,* 2018) and is not suitable for highly mobile species and human activities (e.g. fisheries) where restricted spatial management does not work (Bakker *et al.,* 2019). However, it can also be an opportunity to address these conflicts. Multi-use MSP is emerging as a solution to make an *'efficient use of space at sea'* (Steins *et al.,* 2021) by allowing compatible activities to share a common space. In addition to resolving the 'when' and 'where' of Blue Economy sectoral activities, which can be partially addressed through spatial management measures, questions related to 'who', 'how' and 'how much' are pivotal for ensuring sustainability and equity.

2.4.2 Equity, justice, and power

When regulating access to Ocean resources and conducting MSP, it is important to understand that 'sustainable development' means different things to different people (Tafon, 2018) and regulating such common and wild resources involves complex tracking and management of equity (Bennett, 2018) and marine justice (Blythe *et al.,* 2023), including within governing processes. Marine justice relies on ensuring that all communities have the same opportunities. This includes enabling everyone to participate in decision-making, not be exposed to unintended injustices or environmental harm, e.g. from marine resource extraction or developments, and retain the power to enable the changes they choose (Martin *et al.*, 2019). However, it also relies on ensuring that multiple sectors get the same opportunities to thrive without impairing societal goals such as biodiversity and climate targets. In addition, ambitions to have a non-discriminatory and diverse labour market should be supported. Power symmetry (the balance of power among parties, e.g. in political influence, economic strength, and social authority) during planning is crucial to ensure that spatial plans include the socio-economic needs of local communities when balanced against wider societal goals (Gilek *et al.,* 2021). Power asymmetries should be made explicit in the planning process and kept explicit in management schemes (Gerhardinger *et al.,* 2022).

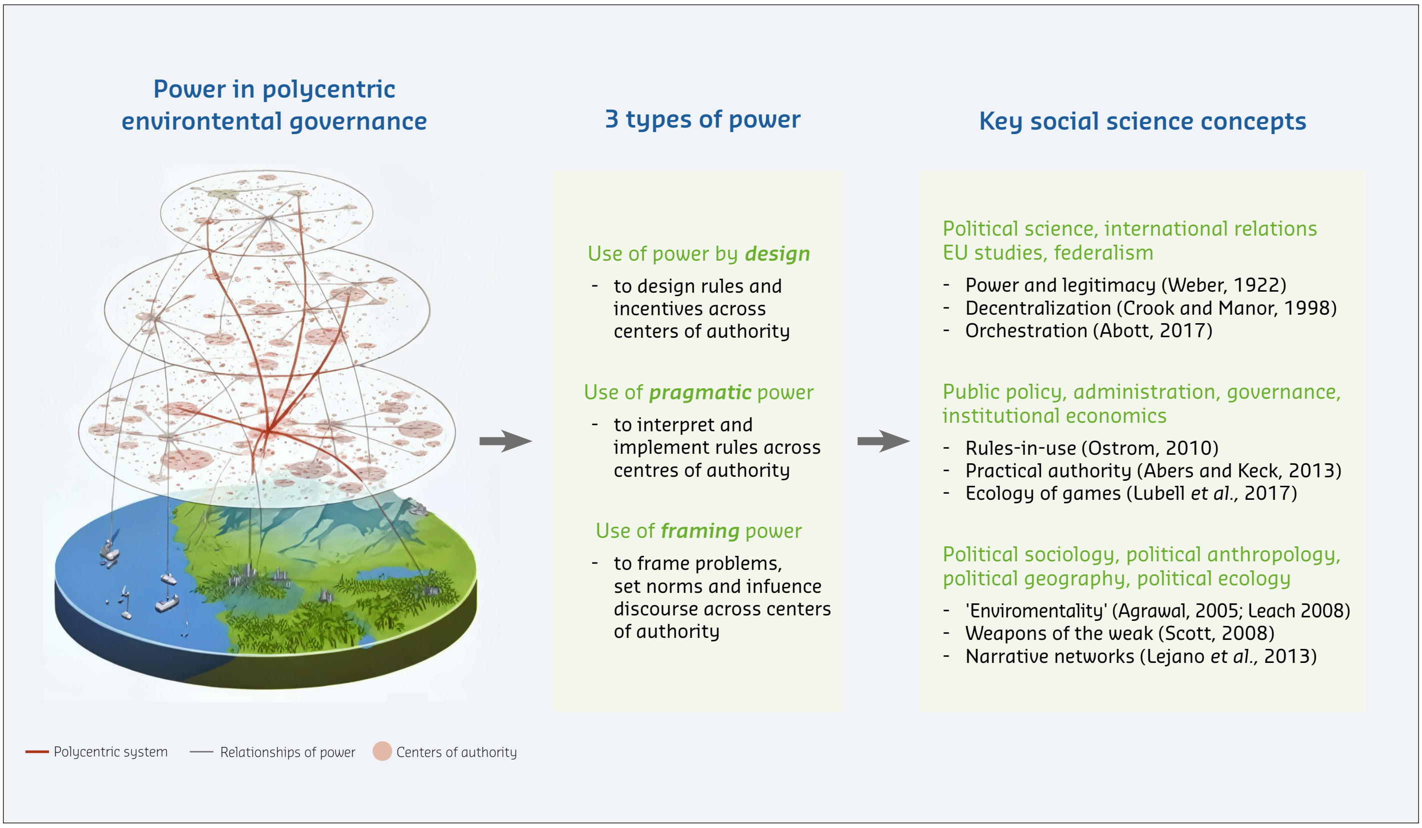
We currently do not know how meeting multiple marine societal goals, through MSP or other means, will impact the integrity of communities neighbouring and depending on these common spaces. We also do not know whether communities will benefit from these spatial transformations. We therefore need to have programs to develop long-term integrated assessment approaches for Ocean policy at all scales, which also enable sustained interactions between researchers and other relevant stakeholders to understand these factors.

As the largest contributor to employment and value added, marine tourism is the principal engine of the Blue Economy in Europe. However, 'economic leakages' (e.g. the loss of tourism income from a local community because profits are returned to offshore investors or jobs created not benefitting locals) can vary greatly between regions (European Commission, 2023). The climate and biodiversity footprint of the sector are also non-trivial. In addition, we also do not yet understand the broader unintended local positive or negative socio-economic consequences of large-scale offshore renewable energy installations beyond theoretical expectations assumed during impact assessments (Glasson *et al.,* 2022).

2.4.3 Alternative governance and decision-making processes

Globally, societal goals interact. We cannot achieve them in isolation, particularly as progressing towards one of these goals might deteriorate others (Lusseau & Mancini, 2019). Diverse and efficient use of marine space and resources to achieve energy security, food provision, biodiversity restoration, and maintain wellbeing requires new multi-scale and collaborative approaches.

Polycentric governance has been proposed as one approach to achieve this. In contrast to monocentric (top-down centralised) governance, it is designed by including multiple governing bodies at multiple scales as shown in Figure 2.2 (Morrison *et al.*, 2019). Polycentric governance can be realised in many ways from global institutions (UN or EU functioning and states' sovereignty) to sector-specific bodies (e.g. regional fisheries bodies), to locally based governance (MPA management committee). This approach is commonly encountered in the co-management of small-scale fisheries, where institutions may set maximum allowable catches and how the fisheries remain below this level is managed by fishers in consultation with other stakeholders (Whitehouse & Fowler, 2018). By potentially spreading power and ensuring accountability, polycentric governance could more likely yield sustainability, including justice, in the management of common-good resources (Lubell & Morrison, 2021). Such approaches are not limited to countries lacking governance capacity. A meta-analysis of hundreds of case studies in the Global North with high governance performance show that such co-management approaches provide better biodiversity conservation outcomes and sustainable exploitations (Newig *et al.*, 2023). Implementing polycentric governance systems that are collaborative and inclusive has been identified as one of seven key principles for enhancing the resilience of social-ecological systems (Schoon *et al.*, 2015), moving away from monocentric governance systems. This realignment of rights and responsibilities in common-resource exploitation can ensure more equitable representations in the management of common marine spaces within and between sectors. Polycentric marine governance is particularly attractive for transboundary MSP where local communities across borders have more common social and ecological interests and priorities than their respective centralised institutions share (Tuda *et al.*, 2021). However, power dynamics remain a challenge for polycentric governance success (Morrison *et al.*, 2019), as power relationships can bias the representations of views in decision centres, as well as in rules design and interpretation (Figure 2.2) (Fortnam *et al.*, 2022).



Use of power by ***design***
- to design rules and incentives across centers of authority

Use of ***pragmatic*** power
- to interpret and implement rules across centres of authority

Use of ***framing*** power
- to frame problems, set norms and infuence discourse across centers of authority

Political science, international relations EU studies, federalism
- Power and legitimacy (Weber, 1922)
- Decentralization (Crook and Manor, 1998)
- Orchestration (Abott, 2017)

Public policy, administration, governance, institutional economics
- Rules-in-use (Ostrom, 2010)
- Practical authority (Abers and Keck, 2013)
- Ecology of games (Lubell *et al.*, 2017)

Political sociology, political anthropology, political geography, political ecology
- 'Enviromentality' (Agrawal, 2005; Leach 2008)
- Weapons of the weak (Scott, 2008)
- Narrative networks (Lejano *et al.*, 2013)

Credit: Morrison *et al.* (2019). CC-BY-SA 4.0 DEED

Figure 2.2 Figure outlining how different power dynamics can interact in polycentric systems of marine governance to affect their effectiveness and ability to yield equitable and just outcomes. Redrawn from (Morrison *et al.*, 2019), see original for additional references.

2.5 Socio-ecological transformation and transformative adaptation

As mass movements such as “Fridays for Future” and the efforts to mainstream climate governance have shown, there is a growing understanding of the necessity for social-ecological transformation, i.e. a fundamental, system-wide reorganisation across technological, economic and social dimensions, building on new paradigms, goals and values (IPBES, 2022). Yet, both the design and goals of such a transformation are socially contested (Adloff & Neckel, 2021). Debates focus particularly on whether structural changes in our economic system are required, or whether only marginal changes in (environmental) policy and the use of technical solutions are sufficient (Nightingale *et al.,* 2020). Current policies focus primarily on technical innovation as an answer to the socio-ecological crisis (Klepp & Hein, 2023). This includes the idea that steady economic growth can be maintained through technological progress that does not destroy the environment. The sustainable Blue Economy debate mainly uses this logic, aiming to maintain growth through the exploitation of marine resources without causing ecological harm (Ertör & Hadjimichael, 2020). However, permanent growth is not physically possible despite continuous innovations and more efficient forms of resource use (Kurz, 2019). The ‘rebound effect’ persists: our use of resources has continued to increase and has cancelled out progress and savings made due to more efficient technologies. Boats have become bigger, fishing power has grown and spread into areas previously out of reach, and mineral extraction is considered in places we are just discovering (Jouffray *et al.,* 2020). A more far-reaching transformational approach calling for structural social change and social innovation is needed that reconsiders paradigms, assumptions, deeply held beliefs and the way humans relate to nature, which is currently only treated as a commodity (Nightingale *et al.,* 2020).

Transformative adaptations are restructuring, path-shifting, innovative, multi-scale, system-wide and persistent measures and interventions (Fedele *et al.,* 2019). We could choose to adapt to our changing environments in ways that are different from previously chosen unsustainable pathways. Since specific societal structures and the still prevailing paradigm of continuous growth have led to these crises, we need deep, structural changes to solve our current problems. However, activating deeper leverage points that address rooted structural issues is significantly more difficult than enacting ‘shallower’ techno-centric solutions (Abson *et al.,* 2017).

A concrete example of how transformative climate change adaptation might be a catalyst for social innovation and gender equality on land and sea is ‘gender-transformative climate change adaptation’ (Resurrección *et al.,* 2019). Mainstream climate mitigation and adaptation approaches are based on the same exploitative structures of humans and of natural resources that have led to today’s socio-ecological crisis. Gender-transformative adaptation necessitates paying attention to gender balance in planning and decision-making bodies at different administrative scales and considering labour issues at the forefront of climate risk analyses. Gender-transformative adaptation shows the deep interlinkages of social and ecological exploitation and can be used to tackle unsustainable human-Ocean relationships in times of social-ecological crisis. This is important because the Ocean is undergoing drastic and continuing changes, and Ocean sector employment is highly gender structured (Blythe *et al.,* 2023). It also links to Ocean science itself, as the improvement of employment opportunities for women in marine science is crucial, also for more effective conservation efforts (Giakoumi *et al.,* 2021).

2.6 Tools and enablers

Increasing Ocean literacy is critically needed as we are becoming globally disconnected from nature (Soga & Gaston, 2018), with Ocean-related topics being under-represented in our experiences of nature and in curricula (Costa & Caldeira, 2018). An Ocean literate person can understand the importance of the Ocean for humankind. They are able to communicate about the Ocean in a meaningful way and can hopefully behave more responsibly towards the Ocean and its resources. Concern raised by an Ocean literate public may also put additional pressure on governments and corporations to act. Ocean literacy helps to make the invisible more visible. However, Ocean literacy campaigns should target all of society, moving away from youth- and western-centric programmes (Kelly *et al.,* 2022).

To better understand the evolving interaction between humanity and the Ocean and to work towards the required transformations, we need data. However, not all data are or must be generated specifically by and for scientific research. Citizen science initiatives can serve as a means to enhance Ocean literacy, and can gather scientific information, including on marine biodiversity (e.g. within-species, functional, ecological and microbial diversity), fresh water (e.g. aquatic pollution, such as contaminants of emerging concern (CECs)), and climate (e.g. physical properties such as coastal temperature). These initiatives have the capacity to promote participatory management of common resources, governance and decision-making, which can enhance the scientific capacities of citizens (Göbel *et al.,* 2019). An increasing number of citizen science initiatives are being established across Europe, with most registered on the EU citizen science platform[40]. For example, in the well-established citizen science initiative Coastsnap, volunteers contribute pictures of the coast at fixed stations to identify long-term changes along European coastlines (Harley & Kinsela, 2022).

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[40] https://eu-citizen.science/

Credit: Sheila Heymans

Coastsnap images from the Ostend beach station in July 2021 and March 2022

In addition to robust approaches able to verify that reported data are scientifically valid, successful citizen science projects require a medium- to long-term approach, and investment in training and retaining volunteers. The emotional, learning, and social aspects of engagement should be increasingly considered in monitoring the impacts of these participatory approaches, rather than only the number of volunteers involved in data collection (Phillips *et al.,* 2019). This includes, for example, assessing the changing knowledge and relationship built with the studied organisms or the cohesion and dynamics developed within the group of participants. Such long-term and adaptive citizen science projects still need to be developed in Europe and could learn from successful initiatives such as Reef Check Australia (Schläppy *et al.,* 2017), which uses an adaptive project to assess opportunities, and revisit protocols and the focus of the initiative to incorporate the vision of participants and improve community engagement throughout the project lifespan.

The widespread use of the internet, and in particular social media, has created opportunities for collecting multimedia ecological data generated incidentally by humans (known as Internet Ecology, or iEcology). An example is the assessment of seasonal migration patterns of salmon based on Wikipedia page view frequency (i.e. it is likely that people will view the pages more often when they actually see the salmon, indicating when they are migrating) and on images uploaded to social media (Jari *et al.,* 2020). These tools can potentially be used for ecological monitoring and have been used to identify priority conservation areas (Giovos *et al.,* 2018) and to track phenology[41] changes (Mittermeier *et al.,* 2019). These are particularly useful for socio-ecological research, by e.g. complementing data-poor recreational fishing studies (Monkman *et al.,* 2018) or investigating human habits and perceptions (Sbragaglia *et al.,* 2022). Despite the potential, iEcology-derived data have biases, subjectivity (e.g. unequitable reporting due to users' preferences for some species), non-randomness (e.g. data availability is related to human population density) and potential ethical issues (e.g. privacy) that need to be considered. The lack of accessibility of the offshore marine environment also limits the success of citizen science and iEcology projects in these areas, thus most deal with iconic species of marine megafauna (mammals and birds), coastal biodiversity and pollution (Garcia-Soto *et al.,* 2021).

The recent EU Open Science policy[42] and the increasing availability of reusable data (following the FAIR principles) is rapidly increasing the amount of Ocean-related data available for research, with a growing consideration for data related to human dimensions, which raises specific challenges. This vast body of information is also fuelling the application of artificial intelligence in social-ecological research. For example, the use of machine learning to process and analyse large datasets, removing the need for manual intervention, could be a rapid and cost-effective tool for advancing and widening Ocean monitoring (McClure *et al.,* 2020). Going further, deep learning could also help identify some cultural preferences in marine research and conservation by analysing the social media and citizen science interactions of different profiles (Havinga *et al.,* 2023). Improved data availability supports the development of mechanistic models as well, which can explore the current state of human-Ocean relationships as well as simulate and forecast future scenarios with different degrees of uncertainty (Macher *et al.,* 2021). It can also be used in living labs, i.e. co-created inter-sectoral fora that can explore wider social-ecological challenges, which commonly operate though iterative feedback cycles aiming to be sustainable in the long-term (Hossain *et al.,* 2019). Further exploring innovative frameworks to allow transdisciplinary collaboration while addressing social-ecological conflicts should be a priority in marine research.

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[41] Phenology is the study of the timing of recurring biological events (e.g. seasonal migrations or spawning), the causes of their timing in relation to biotic and abiotic forces, and the interrelation among phases of the same or different species

[42] https://research-and-innovation.ec.europa.eu/strategy/strategy-2020-2024/our-digital-future/open-science_en

2.7 Recommendations

2.7.1 Recommendations for policy and management

- Ensure that the evaluation of marine strategies more formally includes ecological, economic, social, and cultural values. These evaluations should, in return, inform policies on marine protection, fisheries management, coastal planning, climate strategies, and cultural preservation, ensuring harmonious coexistence with our marine environment;

- Increase capacity for inter- and transdisciplinary research, including by: i) explicitly designing inter- and transdisciplinarity into research calls, applications and review processes; ii) funding the developmental stages of interdisciplinary collaborations and interactions with stakeholders, as well as ensuring that the relationships can be maintained post-project, and iii) enabling training for collaboration across disciplines and beyond academia, including for Early Career Ocean Professionals;

- Develop decision-making innovation laboratories dedicated to Ocean policy issues to test the impacts of management strategies under alternative future scenarios, and track, audit and analyse the effects of implementing diverse decision-support approaches (e.g. participatory approaches);

- Analyse and reform Ocean governance to ensure equity in the participation of various communities and inclusion of values and knowledges. This includes the workings behind decision-making, such as the role of science and scientists, the voting systems or the representativity of powerful actors;

- Consider Ocean science-policy interfaces as places to address conflicts, notably through science diplomacy, being aware that Ocean governance is influenced by and influences the emergence and resolution of conflicts at many scales;

- Strengthen the connections between research on the social, economic, political and legal dimensions of Ocean governance, which would require reforming the bodies mandated to regulate and coordinate the multiple uses of the Ocean, to include all these dimensions and avoid fragmentation and silos;

- Recognise the need for structural change that is not based on growth paradigms and that acknowledges the vulnerability and finite nature of Ocean resources and design actionable and testable roadmaps for a stepwise transformation towards the proposed alternative frameworks. This requires: i) understanding that humans are part of the marine ecosystem, ii) the development of Blue Economy policies that allow for structural and equitable change for the effective protection of the Ocean, as well as communities and their livelihoods, and iii) marine protection mechanisms that are culturally and socially appropriate and do not reinforce (old or new) social inequalities; and

- Use complementary criteria such as emotional, learning, and social aspects to monitor engagement in funded citizen science projects, rather than using assessment metrics based only on the number of participants or volume of data gathered. Also develop auditable citizen science funding programs and calls that enable the medium- to long-term execution times needed to effectively engage volunteers in the scientific process.

2.7.2 Recommendations for research and monitoring

- Develop recurrent evaluation methods that encompass a comprehensive spectrum of values associated with the marine environment and the rich tapestry of maritime cultures, and that acknowledge the complex feedback between the Ocean and society, while recognising the multifaceted economic, social, and ecological interactions;

- Advance inter- and transdisciplinary thinking and support cross-cutting methodological development. This will require the development of new metrics for success and encouragement of academic journals to better value inter- and transdisciplinary outputs. In order to better value inter- and transdisciplinarity in academic career development, institutes and departments are needed where this is normal;

- Apply known methods to estimate where, when, and by whom Ocean values are used, to gather data and better describe these values and their interactions with ecosystem dynamics, economy, and policymaking processes. There is a need to integrate together these many strands of insights coming from different disciplines to build a coherent model of current human needs from and interactions with the Ocean;

- Further investigate the current Blue Economy narratives underlying the development of economic sectors and Ocean policies (including the use of Marine Spatial Planning) and their consequences on society. Methods should be developed to analyse the future of the Blue Economy across interacting sectors, including how it will adapt at multiple scales;

- Support the long-term development of integrated assessment approaches in support of Ocean policy at all scales and enable sustained interactions between researchers and other stakeholders;

- Ensure that people are considered as part of marine ecosystems within research, and understand how their efforts to use the Ocean to improve their wellbeing can be fostered in Ocean governance practices; and

- Develop research on power relations and different narratives of human-Ocean relations and define how to include these factors in inter- and transdisciplinary research and in policymaking, because cultural and political factors are central to marine conservation and transformative change.

3

Ocean and Climate

Credit: Ben Mack, Pexels

The Ocean is an intrinsic component of the global climate system. It interacts with the atmosphere, biosphere, cryosphere and geosphere, influencing climate and weather, carbon and biogeochemical cycles, coastlines, biodiversity, ecosystems, and human societies and economies. The Ocean is also highly vulnerable to the impacts of human-induced climate change, which are already altering its physical, chemical, and biological properties. This has profound and often irreversible consequences for the natural and human systems that depend on the stability of these properties that was achieved throughout the Holocene epoch.

3.1 Introduction

The Intergovernmental Panel on Climate Change[43] (IPCC) assessed the latest scientific knowledge on the interactions between the Ocean and climate in its Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (IPCC, 2019), contributing to the Sixth Assessment Report (IPCC, 2023). These reports provide a comprehensive overview of the observed and projected climate-induced changes in the Ocean and cryosphere, the associated risks, the opportunities for adaptation to and mitigation of climate change, and the knowledge gaps and uncertainties that need to be addressed. The reports also provide policy-relevant information and recommendations to support decision-making and action for various scales and sectors. Within the SROCC (and other IPCC publications), the authors judge the validity of their findings based on an evaluation of the evidence they have and express the uncertainty as a level of confidence. Topics identified as low or very low confidence within the SROCC therefore represent key knowledge gaps that should be specifically addressed by researchers. The current state of knowledge on the Ocean and cryosphere in a changing climate is limited by: i) the shortage of data, ii) difficulty in gathering data due to equipment, ship, and technology constraints, iii) a lack of human resources, iv) the need for a global overview on strategic research gaps and priorities, and v) the need for collaboration. Collaboration is also required at international policy and diplomatic levels, where integration between Ocean and climate agendas should be fostered.

This chapter highlights the marine science needed to address the recommendations from the IPCC reports and to increase the confidence of the IPCC statements on the Ocean in a changing climate. The chapter describes the role of the Ocean as a part of the climate system, the impacts climate change has on the Ocean, and the importance of the Ocean as tool for climate action to achieve the goals of the Paris Agreement[44] and the UN 2030 Agenda for Sustainable Development.

3.2 The Ocean as part of the climate system: a climate mitigator and its major driver

3.2.1 The 4D Ocean

The Ocean covers around 70% of the Earth’s surface, extends to 4,000m depth on average, and holds 97% of the Earth's water volume (around 1,400 million km^3, see also Chapter 4). This volume is not stagnant: major current systems carry water and therefore heat, salt, oxygen, and nutrients horizontally and vertically around the globe. Interactions between the physical, biogeochemical, biological, and geological characteristics of the Ocean occur over different timescales, from as short as minutes to as long as millennia. As highlighted in Navigating the Future V (European Marine Board, 2019), it is thus important to think of the Ocean as four-dimensional, i.e. changing over three spatial dimensions, with time as the fourth dimension.

Variations in Ocean conditions also occur on different timescales, which interact with and overlay each other. These variations can be driven by natural forces such as volcanic eruptions, and anthropogenic forces such as rising carbon dioxide (CO_2) levels outside the Ocean, or by interactions between the different components of the climate system, i.e. atmosphere, hydrosphere, cryosphere, land surface and biosphere. Disentangling these different signals is important for understanding observed changes, e.g. over a time span of decades, and for managing our response to these changes. These multiple timescales must be considered across monitoring, management and conservation activities.

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[43] https://www.ipcc.ch/

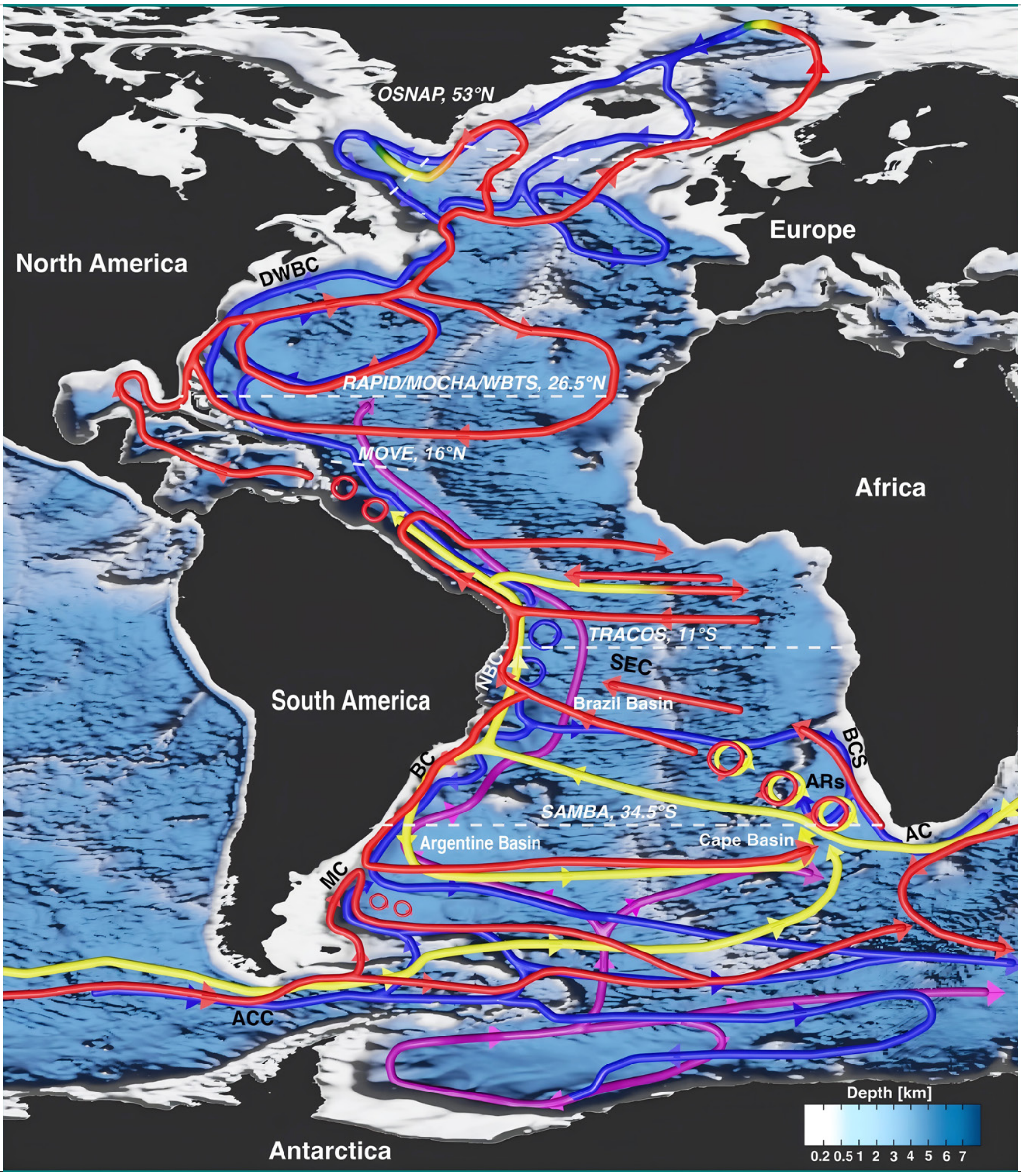
[44] https://unfccc.int/process-and-meetings/the-paris-agreement

3.2.2 Heat and freshwater content

The Ocean is the Earth's main climate regulator. It stores, distributes, and dissipates the Sun's energy, controls evaporation, precipitation and the amount of water vapour held by the atmosphere, contributes to the formation and melting of sea-ice, and stores CO_2.

Due to the large capacity of water to hold heat, the Ocean stores and redistributes vast amounts of heat. Heat exchange with the atmosphere, and the balance between evaporation and precipitation over different geographical areas, causes spatial differences in the distribution of temperature and salinity across the Ocean. Cold saline water is denser than warmer, fresher water. These differences in temperature and salinity generate density driven circulation patterns (called Thermohaline Circulation). The global thermohaline together with the wind-driven circulation (also known as the Great Conveyor Belt, or Meridional Overturning Circulation, see Figure 3.1) redistributes water and heat between the equator and the poles, and causes milder climates in north-western Europe compared to similar latitudes in eastern North America. Large heat changes in the Ocean are occurring more slowly than in the atmosphere, thus the Ocean is a key component of large-scale phenomena such as the El Niño Southern Oscillation[45] in the tropical Pacific Ocean, which shifts temperatures and precipitation patterns around the globe.

The water exchange between the Ocean, the atmosphere, the land and the cryosphere constitutes the water cycle, and is largely driven by solar heating patterns. The large volume of water in the Ocean, compared to the other parts of the Earth, makes it a vital element in the water cycle. Any change affecting the Ocean will induce changes in other elements of the cycle, e.g. a warmer Ocean changes evaporation and precipitation patterns, altering the timing and intensity of extreme weather events such as droughts and floods (Trenberth, 2005).



Credit: Chidichimo *et al.* (2023), CC-BY-SA 4.0

Figure 3.1 Schematic representation of the overturning circulation in the Atlantic Ocean. The figure shows the pathways of surface (red), intermediate (yellow), deep (blue), and abyssal (purple) waters over the bottom topography (blue shading).

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[45] https://www.climate.gov/news-features/blogs/enso/what-el-ni%C3%B1o%E2%80%93southern-oscillation-enso-nutshell

3.2.3 Biogeochemical cycles and the carbon cycle

The Ocean is also one of the key components in the biogeochemical cycles on which life on Earth relies, including the carbon, oxygen, nitrogen and phosphorus cycles. For example, 90% of the carbon that is not stored in geological reservoirs (e.g. rocks, coal, oil, gas reservoirs) resides in the Ocean (Sarmiento & Gruber, 2002). Here, it is mostly found as dissolved inorganic carbon. In the upper Ocean, some of this dissolved inorganic carbon is exchanged with CO_2 in the atmosphere and the atmospheric CO_2 can be sequestered and brought to deeper Ocean areas. For more information on this, see EMB Policy Brief N°. 11 on Blue Carbon (European Marine Board, 2023). Therefore, the Ocean not only regulates climate by taking up large quantities of heat and by modulating the global water cycle, but also by absorbing large quantities of CO_2 from the atmosphere, one of the main greenhouse gases (GHG). Without this oceanic carbon uptake, CO_2 concentrations in the atmosphere would be much higher. The Ocean has already taken up approximately 26% of all anthropogenic CO_2 emissions since 1960 (Friedlingstein *et al.,* 2023).

3.2.4 The oceanic archive of past climate change

Changes in climate are not unique to the present-day but are a recurring characteristic of our planet. Evidence of past climate conditions is preserved in the geological record and ranges from atmospheric gas trapped in ice sheets to fossils preserved in the sedimentary record. In the Ocean, these archives consist of e.g. coral reefs, sediment cores (including their geochemical composition and microfossils preserved within them) and submerged landscapes (e.g. palaeo-shorelines), and new climate archives are still being discovered. Proxy climatic data from these archives allow past climate variability to be reconstructed so that the Ocean's role and response in this variability can be studied (see Box 3.1).

Such data are important to provide a baseline for climate conditions in the pre-instrumental era (usually taken as pre-1850), to assess the performance of climate models and to allow comparison of trends in present-day climate observations to the pre-industrial situation.

Box 3.1: The use of proxy data to reconstruct past climates

We cannot simply go back in time to directly measure past climates. So how do we know that there have been many cycles of changing climate? How can we scientifically compare this with measurements that have been recorded from the late 19th century up until the present? Palaeoclimatologists use proxy data to study past climate, i.e. they use indirect evidence or indicators that can be linked to specific parameters such as temperature, precipitation, or Ocean salinity. Remains of organisms, ice cores, tree rings and sediment cores all contain signatures that can be used as climate proxies. For example, the oxygen stable isotopes preserved in the shells of organisms and corals can be used to determine the water temperature at the time when these creatures were alive. Long time duration records can then be used to derive regional or even global climatic variability and sea-level changes, usually by correlating them with other proxy archives (e.g. ice core data, see Figure 3.2).

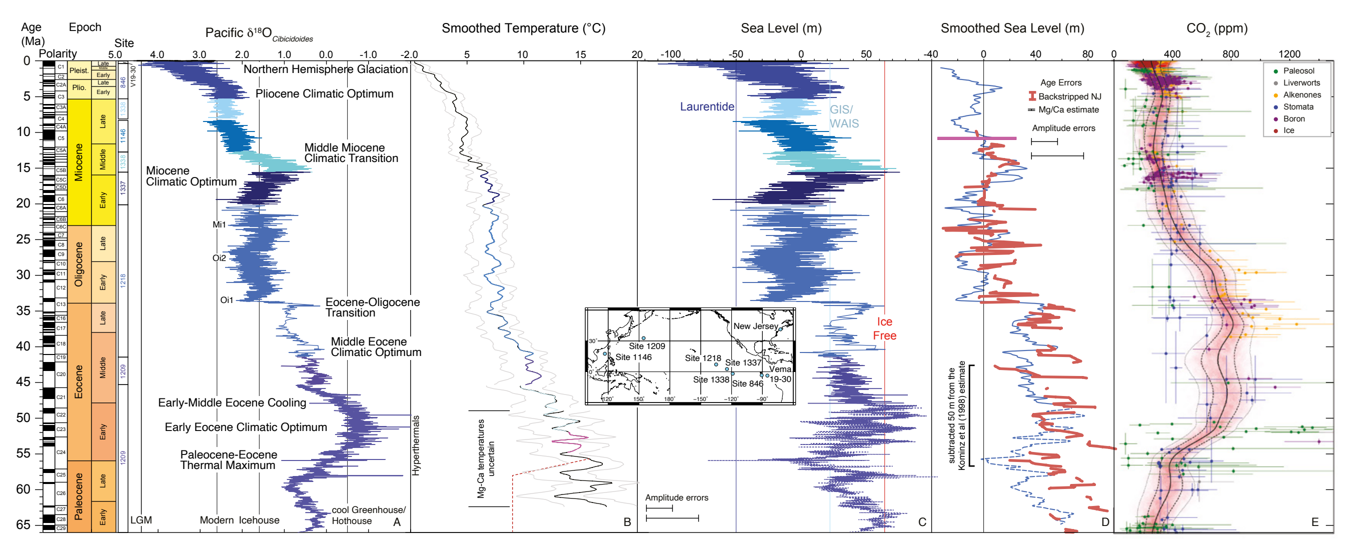

Figure 3.2 Example of how different proxy data are used to derive millennial-scale climate and sea-level records going back 65 million years (Ma) – the present day is at the top of the geologic time scale (0 Ma). (A) Oxygen isotope data from benthic foraminifera; (B) estimated smoothed deep-sea temperature from the calcium/magnesium ratio in Pacific Ocean cores; (C) variation in mean sea-level estimated from (A) and using temperatures derived from (B); (D) smoothed sea-level derived from (C); (E) atmospheric CO_2 variations estimated using various proxies from measurements of Arctic ice cores.

Credit: Miller *et al.* (2020), CC-BY-SA 4.0 DEED

3.3 The Ocean impacted by climate change

Climate change is affecting the Ocean in multiple and interconnected ways, with far-reaching implications for the Earth system and society.

The Paris Agreement aims to *'hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels'*. In recent years, world leaders have stressed the need to limit global warming to 1.5°C by the end of this century. If net greenhouse gas emissions reach zero or below, the increasing trend of global average temperature is likely to more or less stop, and changes at the surface of the Ocean will be reversed: sea surface temperature rise, Arctic sea-ice loss, and surface Ocean acidification and deoxygenation will all reverse within years to decades (Lee *et al.,* 2021).

However, even limiting warming to 1.5°C or 2°C may include scenarios where these warming levels are temporarily exceeded before declining again. Such 'overshoots' can have long-standing consequences for the Ocean, with important impacts on human societies and marine ecosystems. For instance, a temporary overshoot above 1.5°C or 2°C warming would, on the timescale of centuries, have irreversible effects on global mean sea-levels, Ocean heat content, and deep Ocean acidification and deoxygenation. An overshoot above 1.5°C will also have irreversible effects on habitat-forming ecosystems, including coral reefs and kelp forests (Cooley *et al.,* 2022).

3.3.1 Ocean warming, marine heatwaves, and their implications

The vast majority (over 85%) of heat increase in the Earth system associated with climate change since the 1970s has accumulated in the Ocean (see Figure 3.3). The Ocean has consequently warmed at unprecedented rates and will continue to do so (Fox-Kemper *et al.,* 2021). Heat is transferred from the atmosphere to the upper Ocean and then propagates into the deeper Ocean. Ocean warming is fastest in the upper Ocean, which tends to intensify upper-Ocean vertical stratification (Sallée *et al.,* 2021). This stratification is further reinforced in regions where the Ocean surface is freshening (salt content is reducing via ice melt and large river discharge) in response to changes in the water cycle, and has wide-ranging consequences on the transfer of heat, salt, oxygen and carbon from the surface to the deeper parts of the Ocean (known as Ocean ventilation), as discussed below.

Ocean temperature changes can have vast consequences for physical, biogeochemical and ecological processes. For instance, thermal expansion due to Ocean warming causes global sea-level rise and ice melt, which further increases sea-levels (see Section 3.3.5). At the Ocean surface, increased temperature enhances heat and vapour transport towards the atmosphere, which intensifies tropical cyclones (Knutson *et al.,* 2010), mid-latitude cyclones and mesoscale convective systems[46], including meteotsunamis and 'medicanes[47]' in the Mediterranean Sea.

Ocean warming can also impact marine species distribution (see Section 5.5). In addition, Ocean warming is accompanied by an increase in the intensity, duration and frequency of marine heatwaves (Oliver *et al.,* 2021). These are either anomalously prolonged periods of warm Ocean temperatures or extremely warm temperatures over short periods (Smith *et al.,* 2021). These heatwaves can drive mass mortality events which results in a loss of marine biodiversity, such as those the Mediterranean Sea has witnessed over the last two decades (Garrabou *et al.,* 2022). This in turn disrupts the functioning of marine ecosystems, with profound effects on the provisioning of goods and services related to fisheries and livelihoods, coastal protection, nutrient cycling, carbon sequestration, and cultural and recreational opportunities.

In summary, Ocean warming is one of the most prominent and pervasive consequences of climate change, affecting the physical, biogeochemical, and ecological processes in the Ocean, coupled with its interactions with the atmosphere and the cryosphere.

3.3.2 Sea-level rise

Global warming results in an increase in global average mean sea-level. This increase is related to two main components: mass and steric changes (see Figure 3.4). Mass change refers to the addition or removal of water from the Ocean via melting glaciers, and the Greenland and Antarctica ice sheets, or land water storage. Steric change refers to the change in the volume of seawater due to changes in temperature or salinity, which affect its density. The steric effect varies regionally and seasonally, depending on patterns of Ocean circulation and heat exchange. While mean sea-level is currently mainly rising because of the warmer waters (i.e. due to steric change), it is projected that under further climate change, mass loss of the ice sheets (i.e. mass change) might become the dominant contributor to sea-level rise. Acting on higher mean sea-levels, extreme events, such as storm surges, cause more severe impacts to coastlines, which include (but are not restricted to) urban flooding, beach erosion and land loss, salinisation of agricultural regions, and damage to coastal infrastructure (e.g. sewage systems, port and coastal protection infrastructure, coastal roads and railways, tourist destinations) and cultural heritage (e.g. ancient cities and harbours, UN Educational, Scientific and Cultural Organization (UNESCO) World Heritage sites). For this reason, understanding the processes that drive sea-level changes over all spatial (from kilometres to global) and temporal (from minutes to millennia) scales are a must to allow for timely and appropriate adaptation strategies (see Sections 3.3.7 and 3.4.3).

When assessing both present and future sea-levels, the largest uncertainties come from cryosphere changes related to the Greenland and Antarctic ice sheets (Fox-Kemper *et al.,* 2021), as these processes are still not well understood and therefore not sufficiently introduced into global atmosphere-Ocean climate models.

For many coasts, the impact of global average sea-level rise

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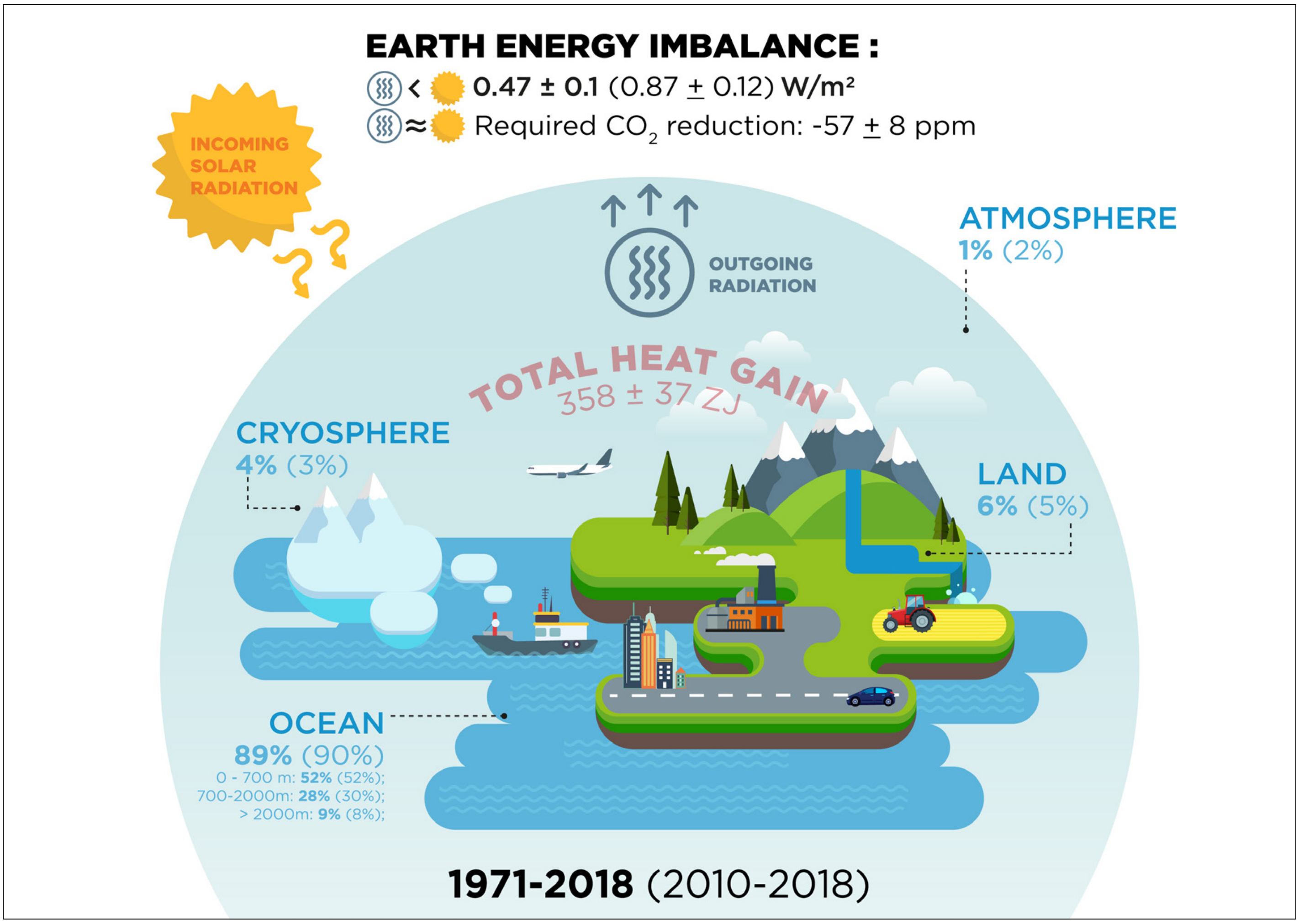
[46] A mesoscale convective system is a complex of thunderstorms that becomes organised on a scale larger than the individual thunderstorms but smaller than mid-latitude cyclones, and normally persists for several hours or more.

[47] A medicane is a Mediterranean tropical-like cyclone or hurricane.



Credit: von Schuckmann *et al.* (2023), CC-BY-SA 4.0

Figure 3.3 Schematic representation of the Earth heat inventory showing the percentage of heat taken up by the different components of the Earth's climate system. At present, a positive imbalance exists with more energy entering the Earth system than leaving it, resulting in global warming. Values in bold are the average between 2006 and 2020, while values in brackets are the average between 1971 and 2020.

depends on how coastal sea-level extremes change. These coastal sea-level extremes, which are shaped locally by bathymetry (i.e. the underwater depth and topography), require kilometre- or sub-kilometre-scale modelling, which is beyond the present ability of climate models (Denamiel & Vilibić, 2023). To completely close sea-level budget projections[48] and include the contributions from processes over timescales of minutes to hours, advanced observing techniques, hazard assessment methods such as Bayesian inference[49] (Calafat & Marcos, 2020) and climate modelling approaches should be developed. The latter will also require the inclusion of surrogate models[50] and machine learning techniques into coastal sea-level hazard assessment techniques. This could be a low hanging fruit for the new European Digital Twin of the Ocean as sea-level rise poses a serious threat to coastal communities, ecosystems, and infrastructure, and requires improved understanding and prediction of the processes and uncertainties involved, as well as adaptation and mitigation strategies to reduce the risks and impacts.

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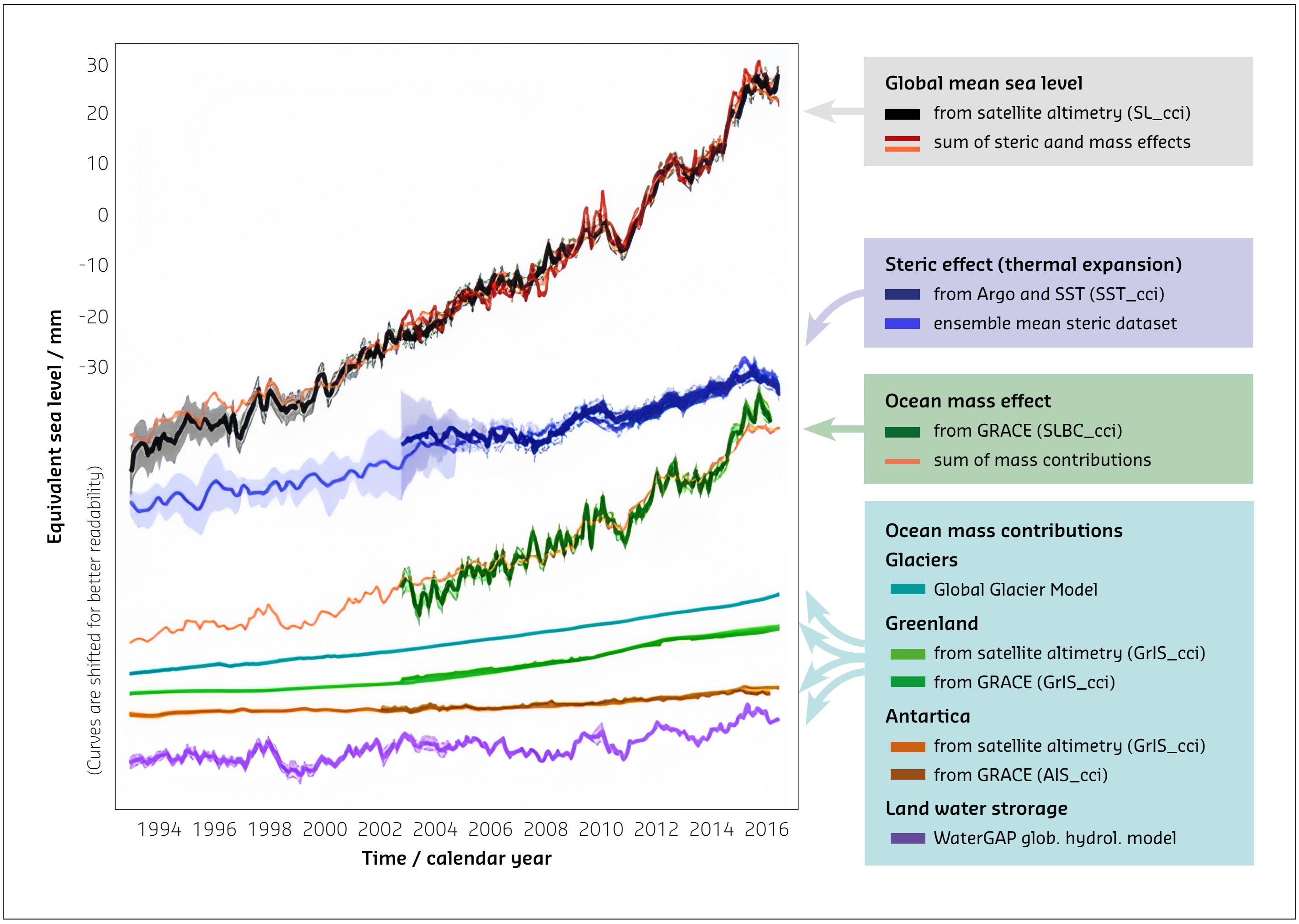
[48] The global sea-level budget is a tool to assess the consistency of the observing systems which are used to estimate global sea-level change and the different elements which contribute to this.

[49] Bayesian inference is a statistical technique where the probabilities of an event occurring are updated when new data are gathered.

[50] Surrogate models are fast-running approximations of complex time-consuming computer simulations.



Credit: Horwath *et al.* (2022), CC-BY-SA 4.0

Figure 3.4 Time series of different contributors to global sea-level change, based on the different elements of the sea-level budget from various observations and models. The figure compares the global mean sea-level anomalies with the sum of the steric component and the individual mass components (from glaciers, ice sheets and land water storage). The steric effect is an important factor in sea-level change, as it accounts for about 40% of the global mean sea-level rise over the period 1993–2016. Argo=ARGO floats, SST=Sea Surface Temperature, GRACE=Gravity recovery and climate experiment (NASA), WaterGAP=global freshwater model.

3.3.3 Impacts on Ocean circulation

Increased temperature at the Ocean surface, and changes in the water cycle and regional wind patterns (Simpson *et al.*, 2016) affect Ocean circulation and ventilation. An increase in upper Ocean stratification (see Section 3.3.1) can affect the vertical exchange of water by both reducing vertical mixing intensity and by slowing the main Meridional Overturning Circulation in the North Atlantic and Southern Ocean (see Figure 3.1). Our understanding of the amount of slowdown of overturning circulation, and the possibility of collapse of these systems, remains hampered by a lack of understanding of the local processes (i.e. kilometre-scale variability of the extreme cooling events in polar regions) driving this circulation (Fox-Kemper *et al.*, 2021). Developing this understanding requires more specific observations, collected at the relevant scales for the process in question, and bespoke modelling.

The reduction in oceanic ventilation can affect heat, carbon and oxygen cycles in the Ocean, as well as regional climate. It may also reduce nutrient uptake in the upper Ocean due to stratification (Gruber *et al.*, 2019) and therefore lower primary production, which together with decreased ventilation may decrease the oxygen content at deeper levels and affect deep Ocean and benthic organisms. See EMB Future Science Brief N°. 10 on Ocean oxygen (Grégoire *et al.*, 2023) and the upcoming EMB Future Science Brief on Deep Sea and Ocean Health[51] for more details. Many Ocean currents and gyres are also sensitive to changes in wind associated with climate change (Fox-Kemper *et al.*, 2021). However, again, detailed understanding of the response of individual Ocean currents is challenged by a lack of understanding of the processes involved, requiring additional high-resolution observations (i.e. at the kilometre-scale) and modelling efforts. Such circulation changes have important local and global implications, e.g. for ecosystems through heat advection and transport of nutrients (Cooley *et al.*, 2022), regional sea-level rise balancing the variability in circulation regimes (Stammer *et al.*, 2013), and for global sea-level rise through the control of temperature changes in the Antarctic ice shelf by local Southern Ocean circulation (Fox-Kemper *et al.*, 2021).

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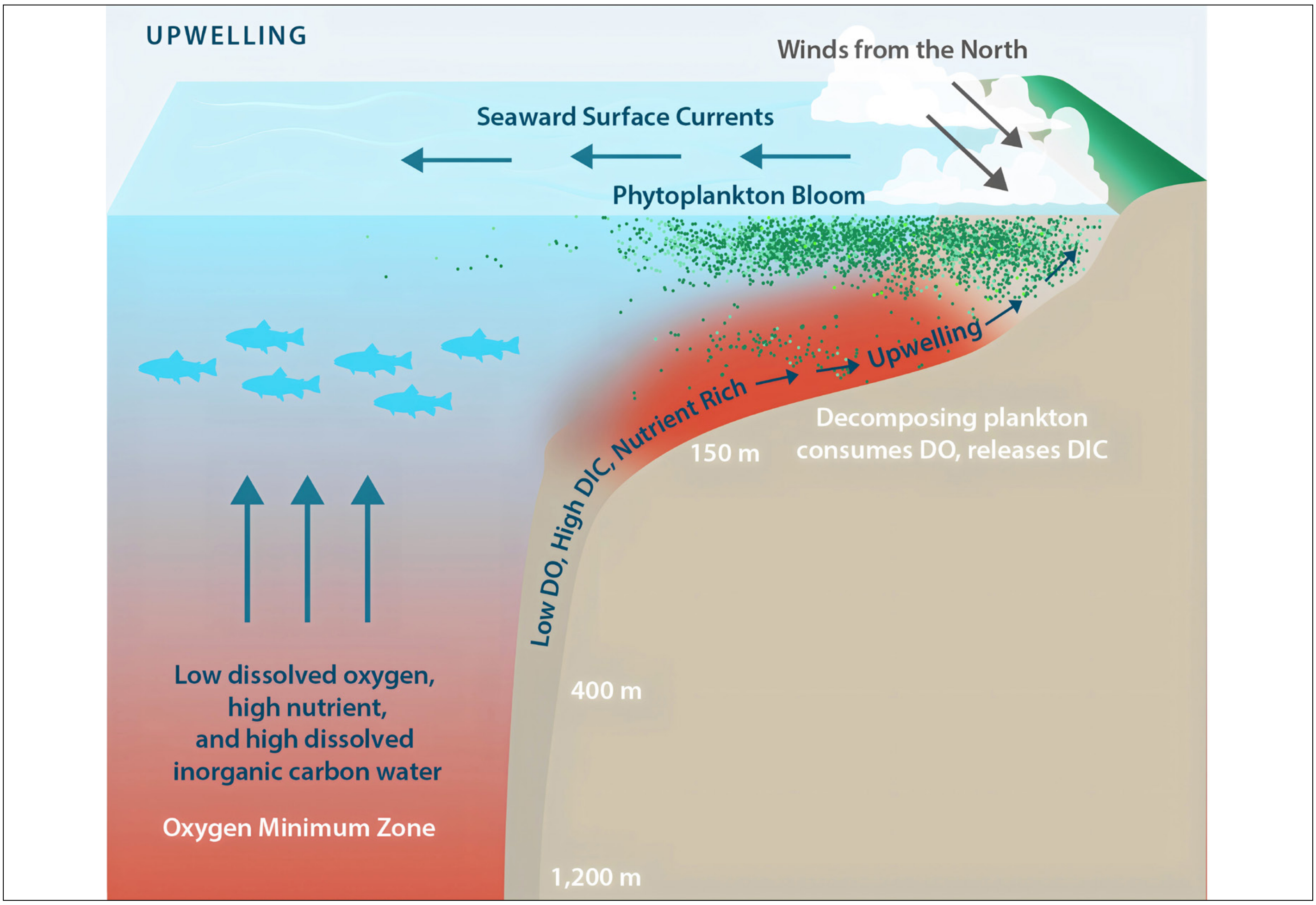
[51] https://www.marineboard.eu/deep-sea-and-ocean-health

3.3.4 Ocean deoxygenation and its implications

The dissolved oxygen concentrations in large parts of the Ocean are declining (termed Ocean deoxygenation) due to a double effect of warming. Warming reduces the solubility of oxygen in seawater, accounting for about 15% of the observed decline, of which 50% occurs in the upper 1,000m (Schmidtko *et al.,* 2017). Warming also changes stratification, circulation, ventilation, respiration rates, and other biological and biogeochemical feedback. These processes are of particular relevance in the fishery-intense coastal upwelling shelf regions where zones of low oxygen already exist due to the combination of high oxygen consumption and weak horizontal circulation (see Figure 3.5) but also in the deeper parts of the Baltic and Black Seas where low oxygen values are already prevalent due to the strong salinity stratification. Furthermore, in coastal areas, an additional driver of deoxygenation is anthropogenic nutrient input (e.g. primarily as fertilisers used in upstream agriculture) coming mostly through rivers, leading to increased microbial respiration, which contributes to the loss of oxygen (see Figure 3.5). Current estimates suggest a decrease of 0.5-3% in oxygen content over the past 50 years, with projections suggesting a further 2-3% decrease by 2100 (Grégoire *et al.,* 2023). Our understanding of the biological, chemical, and physical processes controlling oxygen dynamics is still limited. A better quantification of Ocean residence times (i.e. the time a water parcel or a water mass remains within a certain region of the Ocean before being replaced by new water parcels or water masses, due to currents, heat, rain, winds, etc.), mixing and ventilation rates would allow for individual determination of the effects of physical and biogeochemical processes on oxygen concentrations. For more information relating to Ocean oxygen and recommendations to further our understanding of it, see EMB Future Science Brief N°. 10 (Grégoire *et al.,* 2023).

Ocean deoxygenation affects biogeochemical cycles, marine biodiversity, and the ecosystem services and goods that the Ocean provides (see Chapter 2 and Section 5.2.2 for more on ecosystem services). Ocean deoxygenation also feeds back to the climate system, as it alters the Ocean's capacity to store and release carbon and other greenhouse gases.

The reliable parameterisation of processes and rates in biogeochemical models is essential for quantifying feedbacks related to Ocean deoxygenation within the Earth system. This necessitates controlled experiments and field studies. However, conducting such experiments and studies in the Ocean is not easy, as they face logistical, financial, and technical challenges. Moreover, the high variability of oceanic conditions and the uncertainty in predicting changes due to factors like climate variability, Ocean warming, and acidification add layers of complexity to these studies.



Credit: Chan *et al.* (2019), CC-BY-SA 4.0 DEED

Figure 3.5 Drivers of deoxygenation and acidification in upwelling shelf systems. For more information on these processes and their results, see Grégoire *et al.,* (2023). DO=dissolved oxygen, DIC=dissolved inorganic carbon.

3.3.5 Ocean acidification and its implications

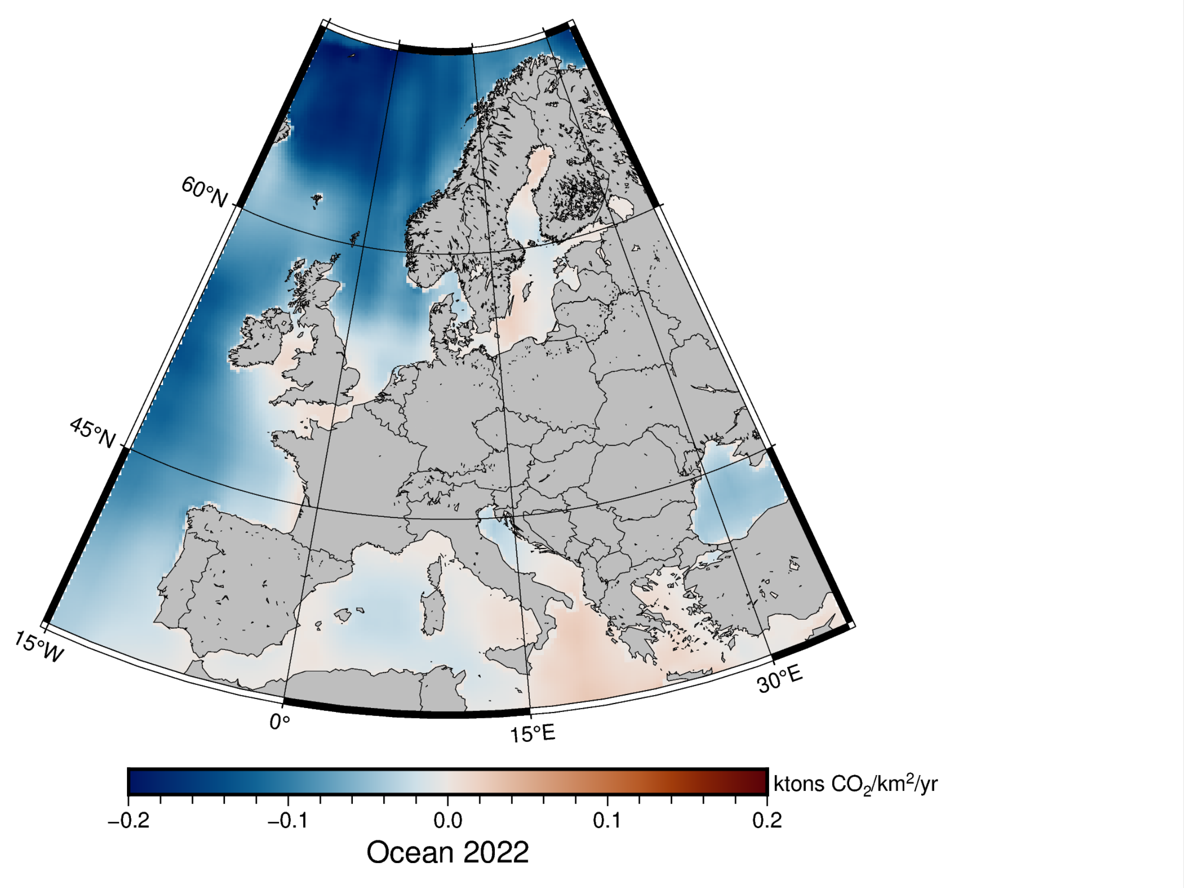
Ocean acidification is caused by the uptake of excess atmospheric CO_2 by the Ocean. When CO_2 dissolves in seawater it causes a decrease in pH, in carbonate ion concentration and in the saturation states of calcium carbonate. Carbonate ions are needed for the production of calcium carbonate shells and skeletons (called calcification) of calcifying marine organisms. As a result, calcification is expected to decrease as acidification increases (Gatusso & Hansson, 2011). Ocean acidification has great biological significance, since it affects the growth of species including plankton, calcifying algae, molluscs, sea urchins, corals, and fishes, as well as the metabolism, reproduction, behaviour, and survival of marine organisms (Doney *et al.,* 2020). Ocean acidification also has implications for the Ocean's role and response in the carbon cycle and the climate system, reducing its ability to take up carbon.

Since pre-industrial times, there has been an average drop in global oceanic surface water pH (which is measured on a logarithmic scale) from 8.2 to 8.1, representing a 30% increase in Ocean acidification (Caldeira & Wickett, 2003). As CO_2 emissions increase, projections suggest that a further decrease of 0.44 units of pH will be observed by the end of the century (Kwiatkowski *et al.,* 2020). This will have severe impacts on marine biodiversity causing population collapses and impairing the capacity of marine ecosystems to deliver ecosystem services and goods to society (Gattuso *et al.,* 2015).

3.3.6 Ocean outgassing and sediment contribution

The Ocean is an important sink for CO_2 (see Section 3.2.3), but climate change and its associated hazards (e.g. marine heatwaves, tropical and extratropical cyclones, Ocean acidification) will put its capacity to act as a carbon reservoir at risk. For instance, large storms can cause cold CO_2-rich deep layers to be upwelled to the Ocean surface and release dissolved gases back into the atmosphere (e.g. Nicholson *et al.,* 2022). Increased freshwater input from melting ice, together with a warming Ocean, can also disturb Ocean stratification, resulting in a reduction in the vertical transport of carbon towards the deeper Ocean (Crueger *et al.,* 2008).

The capacity to store CO_2 is dependent on factors such as temperature (colder water stores more CO_2) and primary production, which is in turn determined by nutrient and daylight availability. This means that there is a difference in carbon uptake between warmer surface and colder deeper waters, between high- and low-latitude regions, and between the open Ocean and shallow coastal waters. Certain areas within European seas even act as a source of CO_2, especially shallow coastal areas but also regions within the Baltic, Irish, Ionian and Mediterranean Seas (Kutsch *et al.,* 2022). Marine heatwaves can damage seagrass ecosystems in shallow coastal waters, releasing large amounts of CO_2 back into the atmosphere (Arias-Ortiz *et al.,* 2018). For more information on the importance of shallow areas for CO_2 storage, see EMB Policy Brief N°. 11 on Blue Carbon (European Marine Board, 2023).



Credit: ICOS Carbon Portal, ICOS-RI[52], CC-BY-SA 4.0

Figure 3.5 Ocean fluxes of CO_2 for Europe and adjacent Ocean areas in 2022. This map shows a strong carbon sink in the open Ocean while coastal areas as well as the Baltic and Mediterranean Seas show a more complex pattern of both sources and sinks.

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[52] https://www.icos-cp.eu/

Methane (CH_4) has a higher warming potential and is, after CO_2, the second most important greenhouse gas contributor directly linked to human activities. Whilst the open Ocean is only a minor source of methane to the atmosphere, other marine methane sources, associated with CO_2 emissions include:

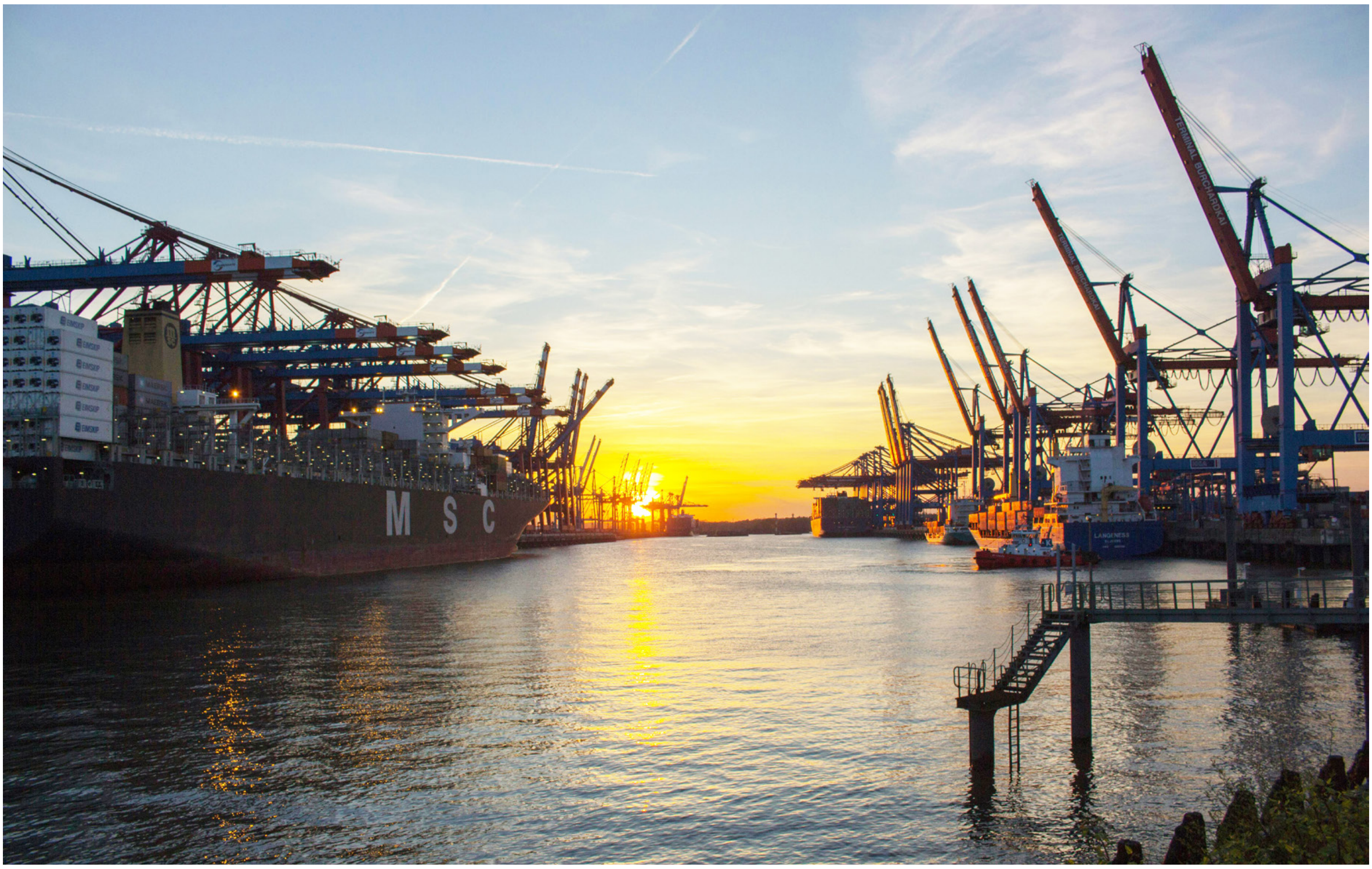
- Dissociation of methane clathrates[53] on continental margins (around 350-5,000m depth), where they are most likely to be found (Future Ocean et *al.*, 2010) due to Ocean warming (Ruppel & Kessler, 2017);
- The release of biogenic methane because of the degradation of organic matter, typically originating from terrestrial run-off, due to climate change-induced changes in coastal sediments (e.g. rising water temperature, eutrophication, oxygen depletion) (Wallenius *et al.*, 2021), which represents around 75% of the marine-emitted methane; and
- The release of trapped methane through the degradation and destabilisation of submerged near-shore permafrost in Arctic regions (Shakhova *et al.*, 2017), with thawing being accelerated by rising water temperatures.

Unfortunately, methane flux measurements are currently scarce in both deeper and near-coastal waters, and little is known about potential methane input into the atmosphere from the Ocean, specifically in shallow coastal areas. Furthermore, the global extent of CO_2 and methane subsea reservoirs are still largely unmapped.

The impact of increased anthropogenic seabed activity (e.g. dredging, offshore infrastructure development) on the release of greenhouse gases into the water column, and potentially into the atmosphere in coastal environments, also needs further study (European Marine Board, 2023), although this is being addressed by the Horizon Europe funded project OceanICU[54].

3.3.7 Impacted coastal areas

Globally, more than two billion people live within 100km of the coast (Reimann *et al.*, 2023) and are increasingly at risk of being affected by the impacts of climate change. Specifically, under a changing climate, coastal areas will be affected by multiple, interacting pressures. These include changes in (extreme) sea-levels (see Section 3.3.2), changes in water properties and quality (temperature, salinity, acidification, deoxygenation, nutrient availability, etc., see Section 3.3.4), and extreme storm surges. These pressures often interact to produce cumulative and synergistic effects. In addition, local extremes of coastal sea-levels could occur more frequently and become more severe and longer, resulting in increased flood risk. This will affect coastal ecosystems (e.g. wetlands, seagrass beds, kelp forests, intertidal flats, beaches and sandy dunes), which in turn affects the habitability of coastal



Credit: Klaus, Pexels

Port of Hamburg, Germany

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[53] Clathrates are natural gas hydrates; a solid similar to ice but with methane trapped by a cage made of water molecules.

[54] https://ocean-icu.eu/

areas by human populations. Climate-induced pressures impact the resilience of coastal social-ecological systems i.e. reduce their ability to persist, adapt or transform when faced with disturbances, while maintaining essential functions such as ecosystem services (Villasante *et al.,* 2023). For example, acidification and temperature increase can severely damage coastal ecosystems, and combined with the increase in (extreme) sea-levels, coasts can become more exposed to waves, storms and (meteo)tsunamis. Eastern boundary coastal upwelling regions are hotspots for temperature increase, acidification and deoxygenation that will affect fisheries in these areas, which accounts for about 20% of global fish catch (Chang *et al.,* 2023). Under rapidly changing climate, and especially with rising sea-levels, infrastructure could become obsolete much quicker than originally designed, primarily affecting countries which have critical infrastructure in coastal areas (e.g. flood defences, energy extraction installations, ports). Knowledge about changing Ocean conditions is needed to improve insight into how coastal social-ecological systems will be affected by climate change and to design optimal strategies for coastal communities to adapt (Villasante *et al.,* 2023).

3.3.8 Tipping points and irreversibility

The climate system does not continue to respond linearly to changes. Tipping points may be reached that put the system irreversibly into a different state, including marine systems (Selkoe *et al.,* 2015). In general, a tipping point is the moment when a system switches from a certain equilibrium state to another. Under an equilibrium state, a system might be pushed away from its equilibrium by an external force, but once the force is removed, the system will recover to its original state. However, if a system is forced too far out of its original equilibrium, it might not rebound, but instead evolve towards a new equilibrium state. Passing a tipping point is almost always irreversible, even when the pressure is removed.

Marine geological archives and terrestrial ice records, coupled with climate models, provide important information on past Ocean-climate tipping points that have been exceeded and their resulting consequences. This is a useful tool to assess the performance of the existing climate models in predicting climate sensitivities. Ten potential future tipping points (e.g. Greenland, Arctic and Antarctic ice sheet and winter sea ice collapse, Atlantic Meridional Overturning Circulation (AMOC) collapse, and boreal permafrost collapse) have been identified for the cryosphere/Ocean system (Armstrong McKay *et al.,* 2022), of which six are expected to occur under a global temperature increase scenario of 1.5-3°C. Such tipping points would have a cascading effect on connected systems such as atmospheric weather patterns and circulation, freshwater availability, coastal flooding, oceanic transport, coastal and deep Ocean biological communities, and ecosystems.

In a similar way to environmental systems, our social and governance systems and management strategies also have tipping points. When the magnitude of the changing conditions becomes too large, existing measures may no longer be sufficient to ensure functionality (e.g. flood defences, freshwater availability, port operations) and coastal policies must change (Haasnoot *et al.,* 2019). The moment where (adaptation) strategies reach their threshold or limit in functionality is known as an adaptation tipping point. It is possible to determine under which conditions adaptation tipping points will be crossed, however, the exact timing of those changing conditions is often uncertain. Ocean science should provide better insight into changing oceanic conditions and provide adaptation signals that indicate when changes in coastal policies are necessary. For more information on tipping points in coastal social-ecological systems, see the Pressures Chapter of EMB Position Paper N°. 27 on Coastal Resilience (Villasante *et al.,* 2023).

When certain thresholds or tipping points are crossed, irreversible and cascading effects on the Earth system and society can result. One example of such a tipping point is that accelerating trends in ice shelf melting could result in the complete collapse of the Western Antarctic Ice Sheet, leading to over 5m of increase in global sea-levels (Naughten *et al.,* 2023), flooding many coastal areas and displacing millions of people. Another is the slowdown of Ocean circulation, which would reduce heat transport towards the poles, leading to colder winters in Europe and North America, and warmer summers in Africa and South America, and affect the monsoon systems, the El Niño Southern Oscillation, the carbon cycle, and marine biodiversity and productivity (see Section 3.3.3).

3.4 The Ocean as a tool for climate action

The Ocean is a critical tool in the fight against climate change, both for mitigation and adaptation measures. There are a number of ways in which the Ocean can enable climate action, including as a provider of crucial information for understanding and tracking climate change, as a source of decarbonisation solutions, and through climate-friendly development and action within maritime sectors. These tools are briefly introduced in the sections below, but for a comprehensive discussion on ‘The Ocean as a Solution to Climate Change’ see Hoegh-Guldberg *et al.* (2023).

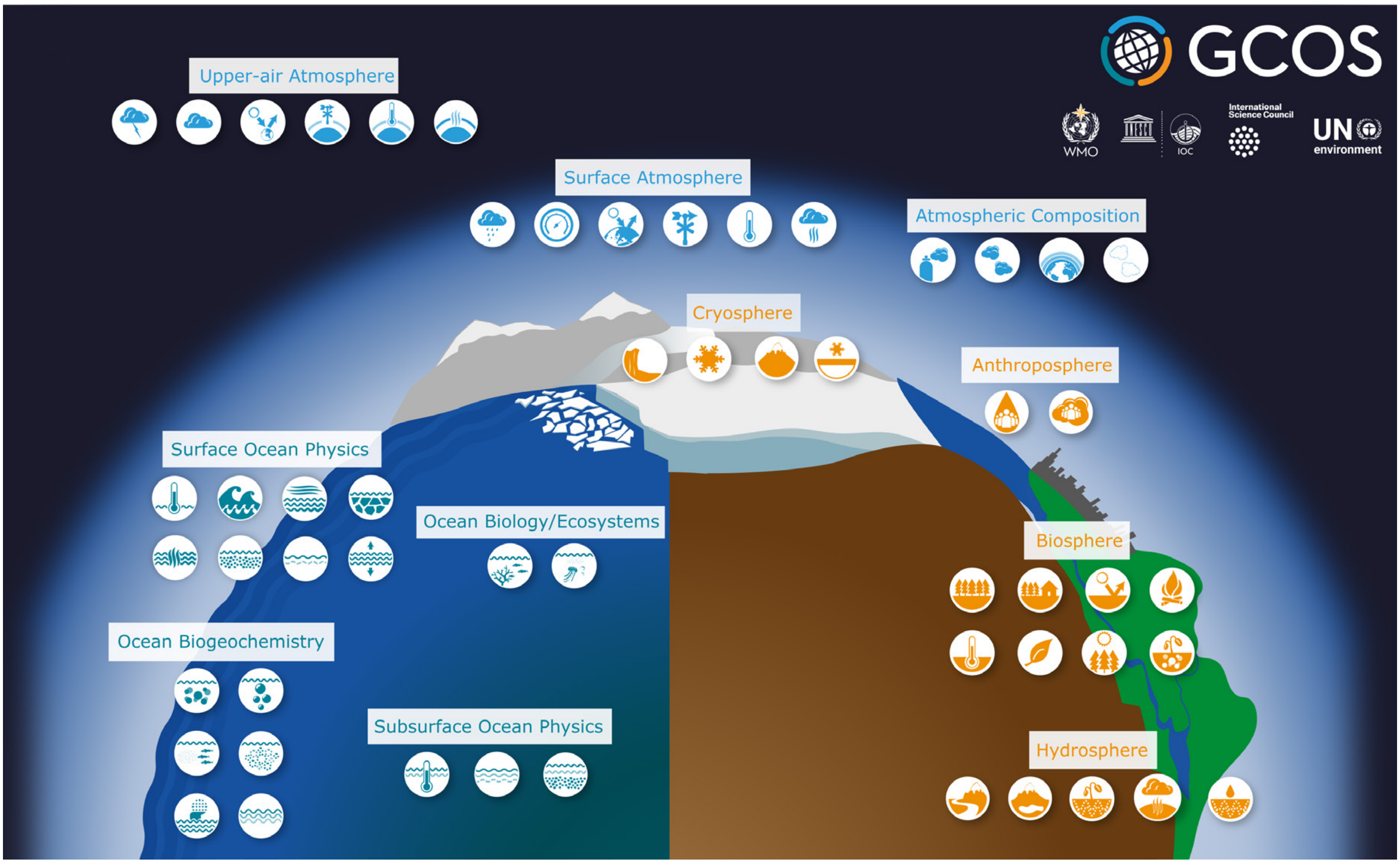
3.4.1 Sharing Ocean data and models

One of the ways to enhance Ocean science for climate action is to exchange data outside the Ocean field. This means sharing and integrating Ocean data with data from other disciples, such as climate, Earth system, social and health sciences. This would enable the development of more comprehensive and holistic solutions for climate action that consider the multiple dimensions and interactions of the Ocean, and its impacts on the Earth system and society. Such data exchange could help to assess the vulnerability and resilience of coastal communities and ecosystems to climate change, to evaluate the co-benefits and trade-offs of different mitigation and adaptation strategies, and to identify best practices and lessons learned from other fields.

The use of open-access computational facilities, e.g. online platforms or services that provide access to high-performance computing resources for processing, storing, and sharing large and complex Ocean data sets is another way to enhance Ocean science for climate action. These facilities enable the use of advanced methods and tools, such as artificial intelligence and machine learning, for Ocean data analysis and modelling, which can help to extract insights and patterns from Ocean data, with the aim of improving the accuracy and reliability of Ocean predictions and projections (Guidi *et al.,* 2020). The European Digital Twin of the Ocean is one element within the EU's Destination Earth initiative[55], which aims to create a highly accurate digital model of the Earth and could be used to create early warning systems and solutions for climate change. The development of these models requires synergies between high-end computing, Earth, Ocean, and atmospheric modellers as well as the community providing the data, with the aim of providing accurate and informative decision-making tools, and advice at local, regional and global scales.

As discussed previously, the Ocean plays a vital role in driving climate and weather patterns globally. As such, it is crucial that we have access to accurate and comprehensive Ocean data to improve forecasting capabilities. This will have numerous societal benefits such as being prepared for and able to mitigate extreme event impacts, making more informed decisions on where to conduct human activities, or how and if we can use resources more efficiently and sustainably, therefore increasing productivity and economic growth. However, to realise these benefits, we need to invest in the collection and dissemination of high-quality Ocean data, and where possible, make data available in (near) real-time.

The Earth system's water and carbon cycles, as well as its energy balance, should be fully monitored by the Essential Climate Variables[56] (ECVs) to comprehend and forecast climate change. ECVs are continuously assessed and revised by global programmes such as the Global Climate Observing System[57] (GCOS) and its panels, who also monitor the performance of the observational networks. The Earth system climate cycles all have a fundamental Ocean component, to which monitoring of the Essential Ocean Variables[58] (EOVs) will also contribute. The UN International Oceanographic Commission (IOC) programme the Global Ocean Observing System[58] (GOOS), and at a European level the European Ocean Observing System[60] (EOOS), aim to coordinate Ocean observations, including those described in the EOVs. One of the initiatives that supports the implementation and operation of GOOS is the Global Basic Observing Network (GBON[61]) for the Ocean, proposed by the World Meteorological Organization (WMO). GBON for the Ocean aims to provide essential and global observations of a number of key ECVs, such as temperature, salinity, sea-level, and CO_2.



Credit: GCOS/WMO, CC BY-NC-ND 4.0

The Essential Climate Variables[58]

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[55] https://digital-strategy.ec.europa.eu/en/policies/destination-earth
[56] https://gcos.wmo.int/en/essential-climate-variables
[57] https://gcos.wmo.int/en/home
[58] https://goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114
[59] https://www.goosocean.org/
[60] https://www.eoos-ocean.eu/
[61] https://community.wmo.int/en/activity-areas/wigos/gbon

Different Ocean observations are coordinated by global, regional, and national networks and marine research infrastructures. European marine research infrastructures (e.g. Euro-Argo European Research Infrastructure Consortium[62] (ERIC), European Multidisciplinary Seafloor and Water Column Observatory – ERIC[63] (EMSO-ERIC), Jerico-RI[64] and European Marine Biological Resource Centre[65] (EMBRC)) are long-term facilities supported by strategic investments, which are expected to have a broad socio-economic impact through technological development, innovation, and improvement of knowledge (OECD, 2017).

Quantifying any ongoing climate change-related hazards requires the measurement of processes, which in turn requires multi-platform observing systems to minimise the uncertainty in the measurements and the standardisation of variables and sampling approaches. In coastal waters, where human populations are particularly vulnerable to adverse impacts, this includes the study of sea-level hazards, heat waves, river plume and freshwater load changes, and saline water intrusions. In the deep Ocean, this includes temperature changes in both the upper and deep Ocean, acidification, deoxygenation, and carbon cycling and storage. At present, the Ocean observing system is not complete or optimal, and there are still many gaps and challenges (see Section 1.4). Investments for further technological developments and for moving towards overall sustainability of the system are needed (European Marine Board, 2021).

Observations cannot look into the future, therefore once we have observed the Ocean, modelling allows us to predict future climate change and its impacts based on different scenarios of GHG and socio-economic development. Global and regional climate models i.e. coupled models that simulate the interactions and feedback between the Ocean, atmosphere, land, and cryosphere, allow us to quantify future climate change based on all possible future societal scenarios. In addition, since climate-induced changes and hazards occur locally, precision matters, particularly for projecting hazards such as extreme sea-levels (Muis *et al.,* 2020). Here, high-resolution atmosphere-Ocean coupled models are required. These are models that resolve the fine-scale (to kilometre- or sub-kilometre scale resolution) features and processes of the Ocean and the atmosphere, such as eddies, fronts, or convection. They can improve the accuracy and reliability of Ocean predictions and projections, especially for local and regional scales, and for extreme events, even if the computational costs of such simulations increase rapidly when the simulations are downscaled. Surrogate models, which use artificial intelligence or machine learning techniques, or 'short' climate simulations adapted to a particular hazard, are used to allow for proper hazard estimates and to approximate the outputs or behaviours of complex models, based on the inputs and historical data. They can reduce the computational costs and time of running complex models and can provide insights and patterns from large and complex data sets. High-resolution climate-scale Ocean modelling requires high-performance computing facilities with the capacity for fast processing, communication, storage, and analysis of vast amounts of data. This necessitates the development of appropriate hardware solutions and software tools to perform the big-data analyses, such as using graphics processing units (GPUs) in for super-computing purposes instead of 'classical' CPUs (Wang *et al.,* 2021).

3.4.2 Mitigating climate change: the Ocean perspective

Greenhouse gas emissions and resulting global warming are the key drivers of climate change, therefore the reduction of CO_2 emissions is critical for mitigating climate change. The Ocean and its key sectors can play a pivotal role in this.

As discussed in EMB Future Science Brief N°. 9 on Offshore Renewable Energy (Soukissian *et al.,* 2023), the Ocean offers the potential for the generation of significant amounts of energy from offshore wind, waves, tides, offshore solar and other resources. Increasing the proportion of offshore renewable energy in our energy mix will help to significantly reduce emissions associated with more traditional carbon-emitting energy generation approaches, even considering the continued increase in energy demand globally.

Marine carbon dioxide removal and carbon capture and storage have also been proposed as active means of using Ocean space and physical properties to remove and store CO_2, although it is noted that controversy surrounds some of the proposed approaches. A new EMB Working Group[66] specifically considers the reliable monitoring, reporting and verification of marine carbon dioxide removal approaches.

At the same time, maritime sectors must also move towards decarbonisation, as presented in Hoegh-Guldberg *et al.,* (2023). The shipping sector must do its part to reduce emissions both through improved efficiency and using alternative lower carbon fuels and propulsion approaches. The food provision sector and in particular aquaculture also needs to take steps towards improved efficiency in feed conversion, avoid feed supply chains involved in deforestation, and move towards use of renewable energy sources to supply their electricity needs.

However, these changes will not take place at the required pace alone. To enable the development of Ocean solutions to climate change, and to ensure that maritime sectors move towards decarbonisation, clear and consistent regulations are needed. These regulations need to be developed and implemented globally in all relevant sectors to ensure that climate ambitions can be realised. We also need to continue research and development activities to support these sectors.

3.4.2.1 Nature-based Solutions

The UN and others have emphasised the importance of conserving entire ecosystems to mitigate and adapt to climate change and

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[62] https://www.euro-argo.eu/

[63] https://emso.eu/

[64] https://www.jerico-ri.eu/

[65] https://www.embrc.eu/

[66] https://www.marineboard.eu/marine-carbon-dioxide-removal

biodiversity loss (Feeney *et al.,* 2023). They identified that conserving and restoring marine ecosystems that act as greenhouse gas sinks and reservoirs helps support the carbon sequestration role of these ecosystems. Simultaneously, protecting these ecosystems also protects biodiversity, improves ecosystem resilience to extreme events and supports the ongoing provision of other ecosystem services. For more information on conservation and restoration specifically related to marine biodiversity, see Section 5.6.

The International Union for Conservation of Nature (IUCN) defines Nature-based Solutions as *'actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature'*.

Four types of Nature-based Solutions have been proposed to mitigate climate change (Eggermont *et al.,* 2015; Riisager-Simonsen *et al.,* 2022):

- Sustainable use and protection of natural marine ecosystems, e.g. MPAs and rebuilding stocks of marine life;
- Improved multifunctionality of managed marine ecosystems, e.g. seagrass and seaweed meadow restoration and shoreline protection;
- Novel, restored or deliberately designed artificial marine ecosystems, e.g. nature-inspired surfaces on built marine infrastructure and low trophic aquaculture; and
- Nature-inspired designs which reduce environmental pressures, e.g. humpback whale fin tubercle-inspired wind turbine blade design for increased efficiency.

One specific Nature-based Solution that is often proposed as a tool for climate mitigation is Blue Carbon. The IPCC AR6 report[67] defines Blue Carbon as *"Biologically driven carbon fluxes and storage in marine systems that are amenable to management"*. The most important issue is the long-term storage of carbon in Blue Carbon ecosystems, which are coastal vegetated ecosystems with rooted vegetation, and marine coastal, continental shelf and offshore sediments. There are also uncertainties around the magnitude of the climate benefits that Blue Carbon ecosystems can provide, but protecting Blue Carbon ecosystems is nevertheless a 'low regret action' that will have many biodiversity benefits (European Marine Board, 2023).

3.4.3 Adapting to climate change: the Ocean perspective

Climate-induced changes in Ocean conditions are having, and will continue to have, a major impact on coastal areas (see Section 3.3.7) and require adaptation strategies if these areas are to remain habitable for human communities. Adaptation strategies should include early-warning systems, long-term coastal planning, and coastal protection solutions across the spectrum of grey and blue-green infrastructure, the choice of which is place- and context- dependent. For more information on coastal protection infrastructure, see EMB Position Paper N°. 27 on Coastal Resilience (Villasante *et al.,* 2023).

To mitigate the damage from climate-induced coastal hazards, early-warning systems are critical (Kushnir *et al.,* 2019). In some coastal areas such as the Venice Lagoon, an operational early-warning system combined with storm surge barriers has been able to protect the hinterland against extreme sea-levels resulting from storm surges, meteotsunamis and other events. This early-warning approach has also protected major European harbours from damage, such as the harbour of Rotterdam on 21 December 2023[68]. Still, some of the most threatened low-lying coasts, such as the Ganges Delta in the Bay of Bengal, with the largest, poorest populations, have no such early-warning systems. Furthermore, even some well-established warning systems, such as the US National Hurricane Center[69], might become unreliable without continually upgrading their forecasting algorithms. Such warning systems need to be operational at different spatial timescales to e.g. increase the reliability of their El Niño predictions, to forecast marine heat waves (with the associated effect on marine organisms), and to predict large circulation patterns (e.g. in the North Atlantic, or Meridional Overturning Circulation) that are the major drivers of European climate.

For coastal adaptation strategies, it is important to have insights into climate change impacts on the Ocean and processes that impact the habitability of coastal areas, particularly low-lying areas that are most at risk, and also into the timing of measures that impact the efficiency of coastal adaptation strategies. Planning, adaptation and mitigation strategies require accurate insight into when and where changes are likely to occur. Hence, we advocate for integrated research where Ocean sciences provide the necessary information needed for planning adaptation strategies. For example, if a seawall or coastal defence is constructed, this investment is related to a certain 'end-of-life time'. However, if sea-level rise increases much faster, the effective lifetime of the construction could be reached earlier. At present, the focus in coastal areas tends to be towards flood safety at a local scale, i.e. each town, city or province plans for their own coastal protection. However, given the large number of people living in coastal areas and the interlinkages between different areas, the focus should shift to be more holistic, aiming for liveability in a broader sense (including freshwater availability, food supply, and assets such as nature and housing). These adaptation developments should be paired with Ocean developments to avoid maladaptation (i.e. adaptation approaches that are harmful and increase, rather than decrease, long-term vulnerability and adaptive capacity).

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[67] https://apps.ipcc.ch/glossary/searchlatest.php

[68] https://www.netherlandswaterpartnership.com/news/maeslant-storm-surge-barrier-largest-moveable-object-world-was-closed-last-night-first-time

[69] https://www.nhc.noaa.gov

3.5 Recommendations

3.5.1 Recommendations for policy and management

- Recognise the importance of Ocean observations in support of international policies and develop long-term sustained funding solutions to support them;

- Support the WMO’s concept of a Global Basic Observing Network (GBON) for the Ocean, which would provide essential and global coverage for some Essential Climate Variables (ECVs). Also ensure that GBON has appropriate financial and technical support for its implementation and operation;

- Develop regulations to support implementation of Ocean-based climate solutions and transform maritime industries to become more climate-friendly;

- Build holistic coastal management plans around the concepts of adaptation and liveability and apply research on adaptation tipping points and their signals to inform policy changes and avoid maladaptation;

- Encourage increased collaboration among nations to develop joint strategies, share resources, and exchange knowledge and best practices in addressing Ocean and climate challenges on a global scale; and

- Emphasise the importance of capacity building programs, training initiatives and educational campaigns to enhance awareness, understanding and engagement on Ocean-climate interactions among diverse stakeholders, policymakers, and the public.

3.5.2 Recommendations for research and monitoring

- Address the knowledge gaps highlighted in the IPCC SROCC report where there is ‘low’ or ‘very low’ confidence;

- Conduct further research on Ocean-based climate solutions to support maritime industries in their move towards decarbonisation;

- Ensure that climate (and thus Ocean) observations are conducted using appropriate methods and instruments to deliver the required precision for the parameter in question and, where possible, to deliver these data in (near) real-time;

- Increase the measurements of biological and biogeochemical parameters, especially in coastal areas and including to map naturally occurring CO_2 and methane, since one of the biggest uncertainties in future climate projections is associated with the response of the biosphere to these changes;

- Research the ‘triple threat' synergistic effects of warming, deoxygenation and acidification (multiple stressor studies), which frequently co-occur because they have a common cause, i.e. the rise of anthropogenic CO_2 in the atmosphere. Moreover, include other stressors, such as pollution and overexploitation which can further exacerbate the impact of acidification and deoxygenation on marine life, habitats and ecosystem services;

- Conduct research to identify relevant signals in Ocean dynamics for the occurrence of adaptation tipping points in the coastal zone and identify how these could be measured in the Ocean and integrated into existing monitoring;

- Develop modelling and observational tools that allow for the better understanding of marine ice sheet instability and to better understand the dynamics of the Greenland and Antarctic ice sheets, specifically related to the potential contribution to accelerated multi-metre sea-level rise beyond 2100 and the possibility to proactively adapt to those changing sea-level rise conditions; and

- Establish and support long-term monitoring programs that track Essential Climate Variables (ECVs) and Essential Ocean Variables (EOVs) over extended periods to capture trends, variability, and potential tipping points, providing valuable data for understanding and predicting climate change impacts.

4

Ocean and Fresh Water

Credit: Maria Orlova, Pexels

Water is required for life and provides essential services to humanity such as food production and climate regulation. Water quality and quantity issues are intimately linked with large societal issues, including social conflicts (Unfried *et al.*, 2022), with more than a third of the world's human population being affected by limited availability of safe drinking water (Schwarzenbach *et al.*, 2010). Therefore, the protection of freshwater and saltwater systems is crucial.

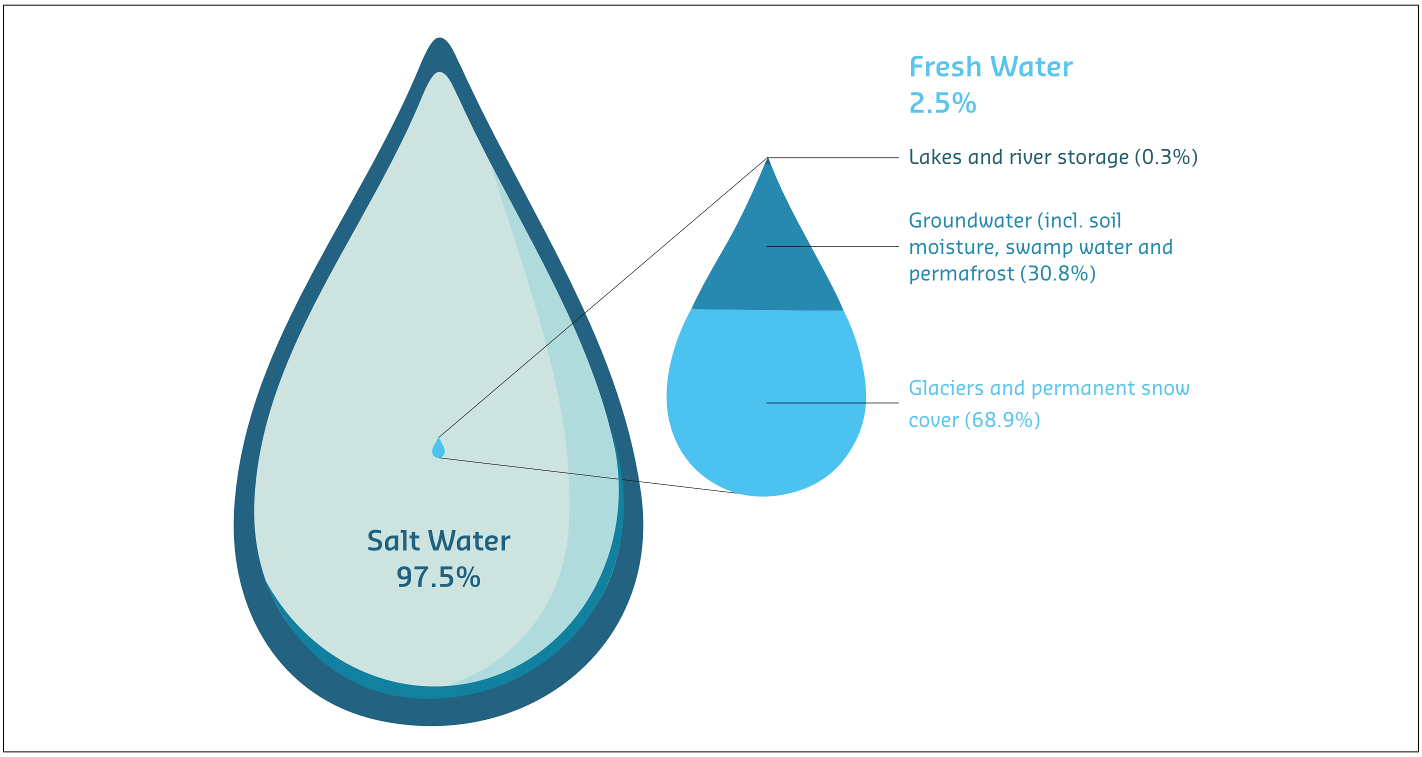
4.1 Introduction

The Ocean, rivers, lakes, groundwater, atmospheric water and ice are all interconnected parts of the global water (or hydrological) cycle and cannot be studied in isolation. The water cycle involves massive fluxes of energy and matter, such as natural and human-made nutrients and contaminants that can be either beneficial or hazardous. The availability of clean water and associated ecosystem services (see Chapter 2 and Section 5.2.2 for more on ecosystem services) are strongly impacted by global warming. Transport of fresh water into the Ocean affects the salinity and density of seawater, potentially disrupting Ocean circulation at regional and global scales (see Chapter 3). As climate change-induced global warming contributes to the accelerated melting of permafrost and glaciers, the transport and supply of nutrients to the Ocean is amplified, and greenhouse gases and microbes (including those that cause diseases) are released. Sea-level rise resulting from global warming also promotes saltwater intrusion into freshwater resources such as groundwater aquifers, with potentially deleterious effects.

Freshwater reserves (i.e. lakes, groundwater, ice caps and glaciers) support terrestrial life on Earth, however, these are naturally scarce: only about 2.5% of all water on Earth is fresh and around 30% of that is stored underground (Figure 4.1).

The transitional aquatic systems at the interface between fresh water and seawater (e.g. river mouths, coastal lagoons, saltmarshes, mangroves) are dynamic and include highly vulnerable ecosystems that provide essential ecosystem services to nearby human populations, such as protection against rising sea-levels and extreme weather events. At the same time, these ecosystems are directly connected to land and therefore strongly impacted by anthropogenic inflows of excess nutrients and pollutants (see Section 4.4).

Ever-intensifying human activities are depleting available freshwater resources, degrading water quality, and altering regional and global hydrological processes, which results in socio-economic challenges, particularly for vulnerable communities[70]. Human activities are pushing Earth beyond the boundaries of what the planet can sustain (Rockström *et al.*, 2009) (see Section 1.2). Therefore, sustainable usage and targeted multi-stakeholder management practices for these invaluable water resources and the ecosystems that host them are crucial.



Credit: Peter Kraal, adapted from Philippe Rekacewicz, Delphine Digout, UNEP/GRID-Arendal[71]

Figure 4.1 Distribution of water on Earth.

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[70] https://www.niehs.nih.gov/research/programs/climatechange/health_impacts/vulnerable_people

[71] https://www.grida.no/resources/5808

4.2 Ocean and groundwater interactions

Coastal areas are where fresh water and seawater connect (Figure 4.2). This interaction across the land–sea interface is important globally for water quality and ecosystem functioning and is profoundly affected by human-driven environmental changes. Challenges in monitoring the dynamic, subsurface environment have so far inhibited our understanding of these interactions and their impacts under rapid climate change.

4.2.1 Freshwater salinisation from seawater intrusion

Coastal human communities rely and depend on coastal freshwater resources, which are under increasing pressure from human activities both directly and indirectly. As a direct effect, rising sea-levels will push seawater further inland, intruding upriver and into freshwater ecosystems such as wetlands. Both the magnitude and in-land reach of this ‘salt front’ are boosted by sea-level rise; it changes living conditions for aquatic fauna and impacts the suitability of this water for consumption and agriculture (Costall *et al.,* 2020). Furthermore, seawater intrusion (the movement of saline water into freshwater systems) also occurs underground, amplified by excessive human extraction of fresh groundwater (Figure 4.2 A and B). This alters the chemistry and quality of coastal aquifers: the high salt content of the intruding water can directly negatively affect (micro)organisms, but also trigger biogeochemical feedback that result in the release of chemicals such as heavy metals and nutrients into the groundwater. Due to the challenges associated with global monitoring, the fate of underground water reservoirs under climate change, and the chemical and biological consequences of underground saltwater intrusion are still poorly understood (Moore & Joye, 2021).

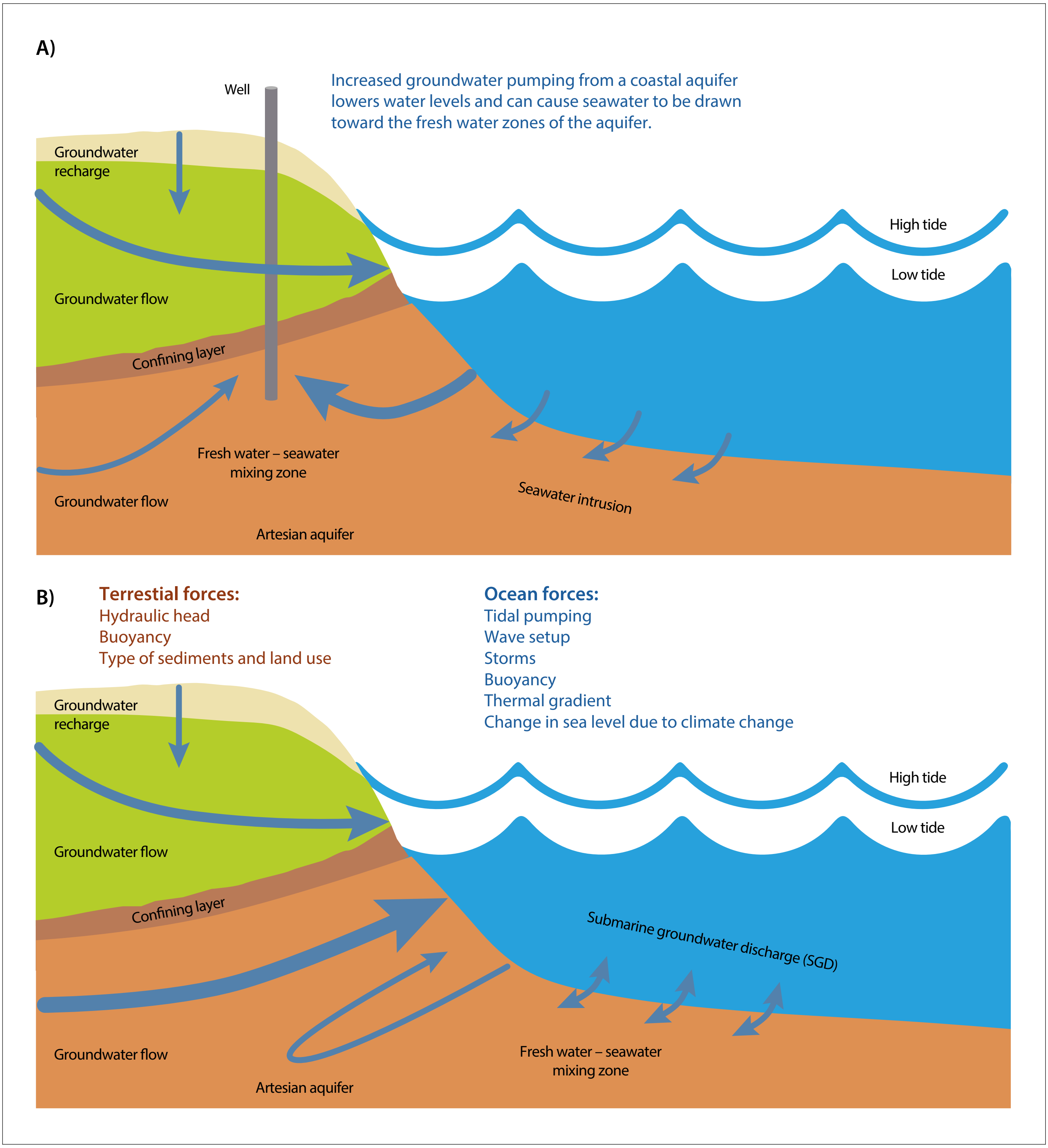
In some cases, salinised groundwater can be further transported to coastal freshwater systems such as wetlands. Increased pumping of groundwater is also driven by climate change, warmer conditions and a need for more water for e.g. agriculture. However, with higher sea-levels, this can also draw more salt water into freshwater aquifers. As such, accelerated climate change and sea-level rise not only create flood risks but also indirectly affect the water cycle and overall functioning of coastal ecosystems. This ultimately leads to challenges in drinking water availability.

Although groundwater management is necessary in all countries to preserve this vital freshwater resource, it becomes imperative in vulnerable areas such on Small Island Developing States (SIDS) and the outermost regions of the EU, where people are heavily reliant on groundwater. Here, higher levels of commitment and immediate management efforts are required to preserve resources. In addition, to improve understanding of the extent and impact of freshwater salinisation, research and innovative solutions on adaptation are also important. To put this into context, some of the questions that need to be answered include how do (micro) organisms deal with changing conditions from seawater intrusion, and how can we develop strategies for sustainable food production approaches that are not only more resistant to salinisation but also counteract it, for instance by reducing the water requirements of crops and thereby reducing groundwater over-pumping (Pulido-Bosch *et al.,* 2018). Our understanding of the large-scale extent and impact of freshwater salinisation will benefit from advances in (real-time) monitoring and reporting that can address the currently scattered and non-harmonised nature of salinity data. Access to high-quality salinity data will also improve model projections of freshwater salinisation (Thorslund & van Vliet, 2020). Measuring conductivity (an electrical measure of salt content in water) is an efficient way to assess salinisation, however broadening the set of monitored parameters (e.g. chemical composition, microbiological population) will greatly enhance our understanding of the impacts of salinisation. In a broader sense, multidisciplinary research should expand from local to global scales and across the whole ecosystem from microbes to humans. We should form partnerships to enable monitoring in countries with relatively small research budgets (Cunillera-Montcusí *et al.,* 2022).

4.2.2 Submarine groundwater discharge: A hidden source of nutrients and pollutants

Submarine groundwater discharge (SGD) is defined as all flows of water from the seabed into coastal waters. Coastal waters can receive either ‘fresh’ SGD as groundwater outflow from coastal freshwater aquifers or ‘saline’ SGD, which is seawater that enters the sediments, interacts with them and finally circulates back to the water column with a different composition (Figure 4.2 B). Fresh SGD delivers nutrients from land, while saline SGD recycles Ocean nutrients. Globally, SGD is a significant source of chemical substances to the Ocean and exceeds the input from rivers in many regions (Santos *et al.,* 2021). For instance, SGD is one of the most important sources of nutrients in the Mediterranean Sea (Rodellas *et al.,* 2015). SGD can have many, contrasting effects that depend on local conditions. It can enhance coral calcification, fuel primary productivity and fisheries, and boost nitrogen removal by denitrification. However, it can also increase eutrophication and cause associated algal blooms, deoxygenation, and localised Ocean acidification (e.g. Taniguchi *et al.,* 2019; Santos *et al.,* 2021).

However, while SGD has been recognised as an important source of nutrients, dissolved organic and inorganic carbon, heavy metals and pharmaceuticals in the SGD of many coastal areas and their effect on ecosystem functioning are still poorly understood (Szymczycha *et al.,* 2020). This is because SGD is invisible in comparison to rivers, and the sources of submarine groundwater and chemical substances are spread over large areas, making them difficult to identify and measure. In addition, we still lack a unified approach for investigating the magnitude of SGD and the corresponding fluxes of chemical substances. Furthermore, we know very little about the impact of climate change on SGD. However, the decreasing volume of ice sheets and increasing intrusion of salt water into coastal aquifers is likely to significantly decrease both the volume and composition of fresh SGD into the Ocean. Increased precipitation can also alter SGD. Therefore, SGD should be considered in monitoring strategies to mitigate pollution and eutrophication (Santos *et al.,* 2021) and should consequently be included in the list of existing monitoring parameters for groundwater according to the WFD for example.



Credit: Beata Szymczycha

Figure 4.2 Fresh water-seawater interactions at the land-sea interface. A) Increased seawater intrusion resulting from groundwater extraction; B) Submarine groundwater discharge (SGD) (i.e. direct groundwater outflow and recirculated seawater). Groundwater recharge occurs as precipitation falls on the land surface, infiltrates into soils, and moves through pore spaces down to the water table. The confining layer is a geological formation, group of formations, or part of a formation that can limit fluid movement above an injection zone. Hydraulic head is the height of the water column whose weight is pushing downwards.

In conclusion, the interactions between fresh water and salt water affect water quality in freshwater reservoirs and coastal areas but are poorly understood. Human activities directly and indirectly increase saltwater intrusion, threatening freshwater ecosystems and reservoirs on which large parts of the global population depend. Therefore, advances in sustained, innovative monitoring are required to understand the deterioration of coastal freshwater reserves by intruding seawater, as well as the effects of groundwater discharge on the (coastal) Ocean.

4.3 Human impacts on freshwater fluxes into the Ocean

Freshwater input from land (i.e. groundwater, meltwater, rivers) into the Ocean is approximately an order of magnitude smaller than the exchange of water between the Ocean and atmosphere, via evaporation and precipitation. However, it is a crucial component in Earth's water cycle, and its role in Ocean health and functioning cannot be overlooked. Rivers transport material from the land to the Ocean, strongly influencing coastal and marine ecosystem services. This transported material includes increasing amounts of human-made substances, such as synthetic chemicals and plastic debris that can cause increased physical and chemical harm (Muir *et al.,* 2023; Wagner *et al.,* 2024), as well as nutrient-rich fertilisers that can cause harmful algal and jellyfish blooms, deoxygenation and acidification. Human activities also affect the magnitude and timing of this transport from land to sea. This occurs directly by extensive river damming that alters land-to-sea transport of dissolved and particulate matter, and more indirectly by inducing climate change and its associated impacts that range from increased rainfall intensity and subsequent (urban) flooding and surface run-off to severe droughts and reduced flushing.

Climate change-induced global warming also affects frozen freshwater reserves. Significant declines in snow cover, glaciers, and sea-ice over the past four decades have resulted in increased fresh meltwater run-off into the Ocean, which changes salinity and stratification and impacts global Ocean circulation (Jahn & Laiho, 2020) (see Section 3.3.3).

4.3.1 Global warming and altered freshwater fluxes in polar regions

Glaciers and permanent snow and ice cover account for as much as 70% of Earth's fresh water (Figure 4.1). This reservoir is highly sensitive to global warming and plays a crucial role in modulating climate and sea-levels. The Arctic region is warming much faster than the global average, and at 2°C of global warming, the Earth's frozen regions will suffer irreversible damage (ICCI, 2023). As a result of the warming, polar marine ecosystems face reduced sea-ice coverage, increased meltwater fluxes and associated nutrient run-off, increased Ocean acidification (see Section 3.3.5), and changes in phytoplankton communities (Bindoff *et al.,* 2019). In addition, large amounts of previously frozen organic and inorganic matter, GHGs and microbes (including pathogens) are released into the environment and eventually the Ocean with currently very poorly known impacts (Yarzábal *et al.,* 2021).

Credit: Lars Grübner, Alfred-Wegener-Institut, CC-BY 4.0

Impressions of the Antarctic ice, taken during the Polarstern expedition ANT-XXIX/2 (supply trip from Cape Town to Neumayer Station III).

The rate and extent of major ice sheet melt in Antarctica and Greenland is an important source of uncertainty in climate and sea-level predictions, which may lead to underestimations of both future rates and impacts of ice sheet collapse (Pan *et al.,* 2021). Warming of the Southern Ocean will accelerate ice sheet flow into the Ocean with associated ice melt and freshening (i.e. reduction in salt content of the seawater). As such, the Antarctic ice sheet represents a 'sleeping giant' of sea-level rise and accompanying alterations in Ocean circulation, which will impact the distribution of heat, carbon, and nutrients in the Ocean, affecting climate. Observations show that the Antarctic shelf waters are already freshening, resulting in reduced circulation with decreased deep-Ocean oxygen supply (Gunn *et al.,* 2023), which will affect biogeochemical conditions and ecosystem functioning.

The coupling of water reservoirs in Earth's water cycle means that changing ice sheet dynamics directly impact coastal integrity, and the quality and availability of fresh water. Understanding such links (or feedback) in the Ocean-climate system requires accurate knowledge about the underlying physical and biogeochemical processes as well as the rates of change. Besides multi-disciplinary field campaigns, the European research community can contribute significantly to increased understanding by ensuring sustained *in situ* Ocean and satellite observations (e.g. Copernicus Sentinel missions[72]), and through participation in international modelling efforts to reduce the uncertainty regarding the rate of ice sheet collapse and the impact on sea-level rise. Knowledge gaps that need to be addressed to accurately predict the myriad impacts of polar warming include: the effect of ice melt on greenhouse gas emissions (e.g. CO_2 release from melting permafrost), and the response of species and food webs in polar areas to ecosystem changes (Miner *et al.,* 2022), also in light of remobilisation of contaminants and pathogens from thawing soils and melting ice (Langer *et al.,* 2023).

4.3.2 Pathways and impact of pollutants

It is thought that the emergence and proliferation of novel chemical pollutants, or novel entities, has transcended the safe operating space for humanity (Persson *et al.,* 2022) and is challenging planetary boundaries. Human domestic activities, transport, aquaculture, agricultural, and industrial activities and processes can all release a multitude of (synthetic) contaminants into the atmosphere, soil, and water. To understand the fate and ecosystem impact of contaminants it is important to know the concentrations in various reservoirs of the water cycle. However, ultimately, insight into transport pathways and removal processes is key. Here, coastal systems such as estuaries play a crucial role as 'filters' that receive contaminants from freshwater input and regulate their transfer to the Ocean. When fresh water and salt water interact, a multitude of reactions takes place, including sorption, a physical and chemical process by which chemicals may attach to suspended solid particles such as clay and organic matter or even plastic fragments (Laursen *et al.,* 2023). Rapid salinity changes in estuarine ecosystems can induce these chemical-bound particles to aggregate and settle into the sediment bed, becoming a sink for environmental contaminants, harming benthic and sediment-dwelling organisms such as shrimps, crabs, amphipods, polychaetes and sea urchins (Simpson *et al.,* 2013).

On the other hand, sediment disturbance by animals (bioturbation), currents and human activities (e.g. trawling, dredging) remobilise and re-dissolve sediment-trapped chemicals (Bradshaw *et al.,* 2021). Therefore, sediment also represents a secondary source of pollution to the overlying water, biota and potentially to the aquatic food web. Re-dissolved chemicals include 'legacy' substances that were discontinued, restricted or outright banned (i.e. under the Stockholm Convention[73]), but whose persistence, biomagnification[74] and toxicity are yet poorly understood, and which continue to raise human and environmental health concerns long after direct input has decreased or ceased.

Such legacy effects are particularly pressing for persistent contaminants, which remain in reservoirs connected to the water cycle for long periods of time. Examples of this are the sustained toxic algal blooms occurring in the Baltic Sea, which are fuelled by phosphorus released from sediment, even though terrestrial input has strongly decreased (Andersen *et al.,* 2017), or the release of toxic mercury from sediment in the Venice Lagoon decades after its use has been banned (Rosati *et al.,* 2020). Perfluoroctanesulfonates (PFOS), a very stable (half-life of more than 90 years) and hazardous ingredient of per- and poly-fluoroalkyl substances (PFAS), is still present in water and sediment despite its restriction at EU level over ten years ago (Lukić Bilela *et al.,* 2023) (Box 4.1).

Given the interconnection of environmental compartments, it is crucial to assess the role of aquatic colloids[75] sediment, organic matter and plastic particles as vectors (and reservoirs) of legacy and emerging contaminants and consider their incorporation into water quality models for prediction and risk assessment purposes (Maskaoui & Zhou, 2010).

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[72] https://sentinels.copernicus.eu/web/sentinel/missions

[73] https://www.pops.int/

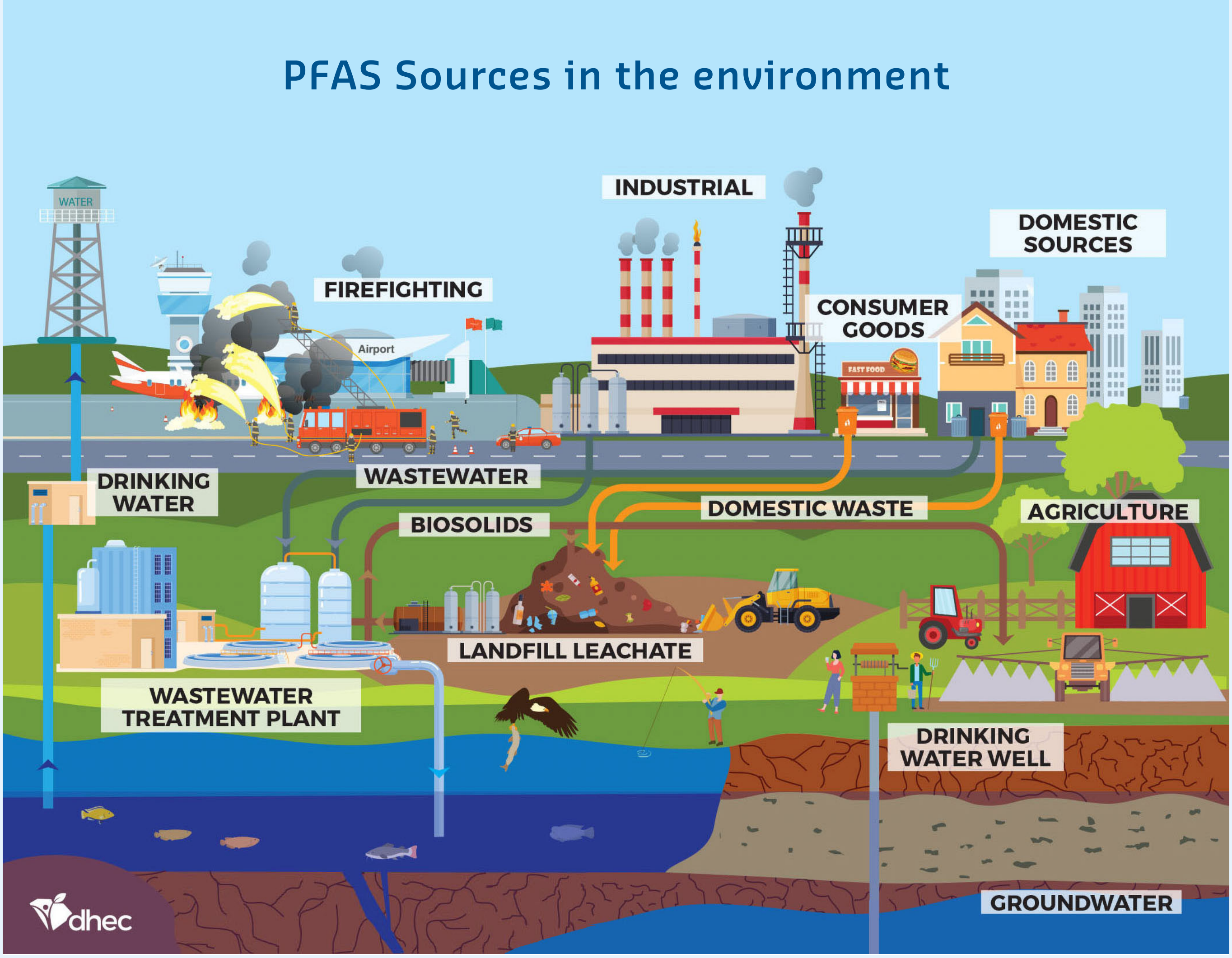
[74] Biomagnification is the cumulative process of storage of chemicals in organisms across the food web through diet

[75] A mixture in which one substance consisting of microscopically dispersed insoluble particles is suspended within another substance

Box 4.1: Release and spread of PFAS in the environment

Per- and poly-fluoroalkyl substances (PFAS) are a vast group of over 4,700 synthetic compounds that have been used for the past 60 years in a wide range of industrial and commercial products (e.g. textiles, cooking pans, cosmetics, paints, carpets, firefighting foams, food packaging; see Figure 4.3). PFAS have been detected in water, soil, food, human blood, and breast milk (Sinclair *et al.*, 2020), and given their persistence and bioaccumulation[76], are referred to as 'forever chemicals' and pose environmental and human health risks. Seafood consumption is the main route for human exposure to PFAS, followed by drinking water and dust inhalation (Cara *et al.*, 2022). PFAS are carcinogenic and neurotoxic to both humans and animals, and may interfere with hormones and the immune system, and disrupt normal brain development (Skogheim *et al.*, 2021).

Regulations and guidelines (SWD/2020/249 final, 2020) are in place to phase out or limit PFAS in the EU. However, the risks and health effects of any substances used as alternatives remain unknown. Research should focus on understanding PFAS transport, transformation, fate, behaviour, properties, concentrations, and biological consequences (Lukić Bilela *et al.*, 2023). Building awareness and knowledge, especially on PFAS mixtures and interactions with other pollutants, is therefore crucial. Although strict environmental guidelines are essential to ensure ecological and public health protection, governments and industry must create economically efficient strategies to meet the established threshold limits (EEB, 2023).



Credit: Used with permission and courtesy of South Carolina Department of Health and Environmental Control

Figure 4.3 Sources of per- and poly-fluoroalkyl substances (PFAS) contamination in the environment

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[76] Bioaccumulation is the accumulation of chemicals in an organism over time.

Contaminants of emerging concern (CECs) are a group of potentially hazardous chemicals and particles for which there may be limited information regarding their environmental distribution, toxicity, or risks (Kumar *et al.,* 2022). They are not traditionally monitored. CECs include pigments, dyes, surfactants[77], human and veterinary pharmaceuticals, illicit drugs, UV filters, hormones, plasticisers, flame retardants, emerging pesticides and the above-mentioned PFAS.

CECs enter the environment through surface run-off from agricultural or urban/industrial areas and the direct discharge of raw sewage or treated effluents from municipal, hospital and industrial wastewater treatment plants. Even though CECs are generally present at extremely low concentrations, they can have severe effects on ecosystem and human health, particularly under long-term exposure. CECs are widespread in aquatic ecosystems, including in the water column, sediment, and biota. CECs affect aquatic biota by disrupting cellular defences, damaging cell membranes, altering DNA and gene expression, disturbing immune responses, and negatively impacting growth, reproduction, and behaviour (Naidu *et al.,* 2016). Moreover, some CECs can also bioaccumulate in the tissue of organisms, including those that are consumed by people (Branchet *et al.,* 2021), such as macroalgae, mussels, oysters, clams, octopus, and fishes (Świacka *et al.,* 2022). Thus, although seafood consumption is beneficial, it can also act as a vector for toxic contaminants. For example, Martínez-Morcillo *et al.* (2020) detected pharmaceuticals in seafood above hazardous limits for young children. CECs can also be transformed in wastewater treatment plants, through chemical and/or biological processes, giving rise to micro-pollutants, which can be more toxic than the original compound. There are over 350,000 commercial chemicals produced globally and these are continuously being released into the environment (Muir *et al.,* 2023). The limited information on their toxic effects is an environmental and human health crisis that needs critical scientific study.

At present, understanding the impact of exposure to mixtures of CECs is in its infancy in terms of research, however, it is also not appropriately considered in monitoring programmes. Future research should take a collaborative and multi-sectoral approach by joining public health, veterinary and environmental sectors, such as that proposed by the One Health concept[78]. Frameworks to regulate or manage CECs are not able to keep pace with their rapid industrial production and discharge. Policy addressing the management of CECs must therefore be rapid and adaptive. CECs that are most likely to have biological impacts need to be identified and rules must be set based on their potential to cause harm (Naidu *et al.,* 2016). Furthermore, standard operating procedures need to be established and adopted to harmonise quantitative assessment of CECs in the environment, which is challenging due to their low concentrations (Manojkumar *et al.,* 2023). Currently, a lack of such data makes it difficult to understand their impacts on aquatic systems and the wider environment.

There are clear challenges regarding water quality management, particularly the prioritisation of substances to tackle when addressing water pollution. The main scientific challenges associated with CECs are:

- The development of new methodological strategies to rapidly document biomonitoring findings and their related health impacts at scale;
- Building a body of well-integrated exposure and toxicological studies to enable the prioritisation of detected chemicals;
- Moving from single-pollutant studies to determining the risk of (common) mixtures of pollutants as they occur in the natural environment;
- The harmonisation of risk assessment approaches applied in regulatory frameworks (e.g. the EU SOLUTIONS project[79]);
- Assessment of the impact of these contaminants on marine ecosystems, including their bioaccumulation and biomagnification across the food chain or the highly intricate networks of interconnected species and processes; and
- Study of the ‘hidden’ reservoirs of persistent contaminants and their sensitivity to disturbance in the context of climate change.

By implementing the existing policies at EU and regional level, countries have put significant effort into achieving Good Environmental Status (GES) through monitoring of the ecological and chemical state of waters under the WFD as well as the MSFD's criteria for eutrophication (Descriptor 5), contaminants in water, sediment and biota (Descriptor 8), and contaminants in seafood (Descriptor 9). Nevertheless, progress in improving water quality by reducing pollution is still far behind targets in some countries.

This may partially be attributed to the slow implementation of EU and regional policies due to, in some cases, the lack of financial resources for, or prioritisation of, the comprehensive monitoring required to produce the data needed by stakeholders and policymakers to propose measures for achieving GES.

Evidence-based monitoring is required to obtain the necessary data to assess the marine environmental state regarding eutrophication and pollution. The costs of more exhaustive identification and monitoring of specific organic pollutants should be, at least partially, financed by producers, following the Polluter Pays Principle, as was proposed in the WFD update by the European Parliament Committee on the Environment, Public Health and Food Safety in 2023 (2022/0344(COD), 2023).

4.3.3 Innovation from waste to resource: pollutant removal and recovery

Despite increasing evidence of the risks of CECs for aquatic life and human health, many of these contaminants are still not included in existing regulation, including the EU Wastewater Directive (Directive 2013/39/EU, 2013) and the Urban Waste Water Treatment Directive (UWWTD, Directive 91/271/EEC, 1991), and therefore

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[77] Surfactants are chemical compounds found in cleaning products

[78] https://www.who.int/news-room/questions-and-answers/item/one-health

[79] https://www.solutions-project.eu/

no safe threshold limits have been prescribed. Meanwhile, some 'traditional' contaminants, such as toxic metals, specific persistent organic pollutants (e.g. dioxins, polychlorinated biphenyls (PCBs)), and excess nutrients from industrial processes and agricultural practices, which are included in regulations and have defined threshold limits, still continue to pose an environmental threat.

While there is a clear need for robust policy (and action) to reduce the emission of contaminants into the environment, the historical and ongoing release of polluting substances calls for development and application of efficient and cost-effective remediation strategies. Here, wastewater treatment plants play a key role in contaminant removal. Currently, however, wastewater treatment technologies cannot fully eradicate contaminants and can only partially remove CECs (Abily *et al.,* 2023). Removal of pharmaceuticals and their degradation products from wastewater remains challenging due to their physical and chemical properties. This has led to hybrid treatment systems that combine contaminant degradation and filtration technologies (Kumar *et al.,* 2022). For example, a wastewater treatment plant that combines sorption and chemical decomposition processes has been shown to effectively remove fifty pharmaceutical molecules of different therapeutic classes and their degradation products from wastewater (Kisielius *et al.,* 2023). The sludge (i.e. the thick residue) from many wastewater treatment plants is recovered and reused in agricultural activities, and hence CECs may be transferred across the value chain and interfere with terrestrial ecosystem services in the medium- and long-term. It is therefore vitally important to invest in technology and optimal treatment procedures to ensure safe quality standards of wastewater and subsequently groundwater, surface and coastal waters. Technologies need to be able to accommodate the larger volumes and wider varieties of chemicals used by an increasing human population and its activities. Management tools such as the European Pollutant Release and Transfer Register[80] (E-PRTR) are essential to assess the release of pollutants into the air, water, and soil from a wide range of industries.

While we are looking for solutions to reduce and remove pollutants in water, we should also consider the potential resource that pollutant-rich waters present and encourage the recovery of essential materials (e.g. nutrients, metals) from wastewater to enable the economic viability and environmental sustainability of wastewater plants as an intermediate step. It is important to consider that future-proofed wastewater management can provide other co-benefits, including alleviating water shortages by recycling water, and by supplying thermal and chemical energy (Kehrein *et al.,* 2020). Nature-based Solutions, circularity and upscaling are key to innovative pollution mitigation. A key incentive for developing nature-based or nature-inspired wastewater treatment technologies is the large environmental footprint of traditional methods, which require large amounts of energy or chemicals. Promising Nature-based Solutions such as algal bioremediation or pollutant removal in constructed wetlands have been field tested but cannot yet compete in efficiency with traditional methods. In that regard, the EC has funded RHE-MEDiation[81], a Horizon Europe Project to test, validate and replicate microalgal-based chemical pollution remediation technologies that will be integrated within existing water/wastewater treatment systems to enhance the removal of heavy metals, pesticides and PFAS. There are also exciting developments in innovative (nano)filtration methods for (emerging) pollutant removal, but maintenance costs currently represent an obstacle (Kehrein *et al.,* 2020). The way forward is to adopt site-specific and sustainable combined methods to recover valuable materials while efficiently removing or degrading hazardous substances.

Credit: ©Bluemater team

The ALGAMATER Project Green Dune photobioreactor installation in Algarve, Portugal. This technology is being further developed within the RHE-MEDiation Project

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[80] https://environment.ec.europa.eu/topics/industrial-emissions-and-safety/european-pollutant-release-and-transfer-register-e-prtr_en

[81] https://rhemediation.eu/

Major hurdles in the widespread adoption of innovative wastewater management practices are cost and scalability. For instance, phosphorus recovered from wastewater is several times more expensive than mining new phosphorus (Mayer *et al.,* 2016), which has its own environmental footprint. The benefit of recovery and reuse of phosphorus includes services that cannot be easily monetised, such as alleviating eutrophication. Thus, lifecycle assessment should be done to assess the overall environmental footprint and cost/value of phosphorus and the total cost of mining versus reuse. Substantial financial support is required to scale-up promising new techniques from the lab to the field, as the financial risks cannot be borne by the research institutes developing the innovations.

Policy and legislative frameworks, including regulations and incentives, are needed to overcome these economic hurdles and share the risks of innovation implementation. Europe can play a pioneering role in line with the EU Zero Waste initiative[82] and the EU Regulation on minimum requirements for water reuse (Regulation 2020/741, 2020). Research that brings together academia and industry is needed. However, change in the public perception of waste and related materials to gain broad public support for reuse is key.

In conclusion, coastal ecosystems are impacted by traditional, legacy, and emerging contaminants, posing risks to aquatic life and human health. Intensive monitoring and research are needed to understand the pathways and impacts of the ever-increasing array of (potentially) hazardous synthetic substances released into the environment, for which manufacturers should bear financial responsibility.

4.4 Cumulative impacts of multiple stressors on aquatic systems

Aquatic ecosystems, particularly those in coastal areas, are affected by a multitude of stressors[83], including excessive nutrient input, chemical pollution, Ocean deoxygenation and acidification, invasive species, and climate change-induced impacts such as flooding, storm surges and sea-level rise (Villasante *et al.,* 2023). These have poorly understood consequences for environmental and human health (Glibert & Mitra, 2022), which increases management complexity. For example, climate change-induced flooding mobilises excess nutrients and persistent pollutants from terrestrial and freshwater reservoirs to the Ocean (Queirós *et al.,* 2023). Furthermore, the toxicity of heavy metals, persistent organic pollutants, pharmaceuticals and pesticides, individual or combined, on aquatic (marine and freshwater) species has been shown to increase under climate change (e.g. Freitas *et al.,* 2023). This is because higher temperatures increase the solubility of chemical compounds in water, while lower pH (i.e. Ocean acidification, see Section 3.3.5) can alter the chemistry of contaminants and enhance uptake by aquatic species. This causes additional stress and raises energy demands, favouring more resilient species and driving ecological changes that require close monitoring. As anthropogenic stressors are primarily addressed individually both in science and policy implementation, adverse effects from interactive stressors are still unclear. In the environment, thousands of chemicals act together in complex mixtures, and these mixtures should be included in the risk assessments of the future (Drakvik *et al.,* 2020). The possible synergistic or antagonistic effects between contaminants should be assessed (i.e. the combination or two or more chemicals to produce a chemical with a total effect that is greater, or less, than the sum of the effects of each individual chemical). Moreover, long- and short-term stressors can affect biological responses in different ways (Freitas *et al.,* 2016), requiring research on the exposure time to a multitude of stressors.

Understanding the relationship between human activities and ecosystem services is essential to ensure effective management of the freshwater-Ocean interface (Villasante *et al.,* 2023). To chart the interactions between different aquatic pollutants and their impacts requires collaboration between pharmacologists, epidemiologist, toxicologists, environmental and social scientists, conservation biologists, and ecologists (Pirotta *et al.,* 2022). Effective communication and the use of consistent terminologies are imperative to avoid misinterpretations across disciplines.

4.4.1 Contaminant release as a consequence of increasing rainfall

Rainfall intensity has consistently increased in both high[84] (around the Arctic ring) and tropical latitudes[85]. Flood frequency and increase in run-off volumes due to increased rainfall disperses nutrients, legacy and emerging contaminants, and pathogens across vast geographical areas (Grannas *et al.,* 2013), with unknown health consequences. The impacts faced by people living in flood zones are already significant (Saraswat *et al.,* 2016), however the risks from exposure to pollutants and disease-spreading pathogens are often only considered after the occurrence of extreme weather events.

Increased rainfall also exacerbates the impact of excessive nutrients in (semi-)enclosed water bodies. For example, in the Baltic Sea two-thirds of the nitrogen and phosphorus derived from intensive agriculture reaches the sea through increased rainfall activity, causing oxygen depletion and boosting harmful algal blooms. Modelling suggests that nutrient reduction targets included in the Baltic Sea Action Plan (HELCOM, 2021) can only be achieved if socio-economic drivers and motivations change in the next decade (Pihlainen *et al.,* 2020).

Rainfall and run-off also disperse persistent organic pollutants, such as phenoxy herbicides[86] and trace metals, which contribute to eutrophication and accumulate in water reservoirs, either at the surface or in groundwater (Mierzejewska & Urbaniak, 2022), with unknown environmental consequences. In addition, rainfall transfers volatile and semi-volatile compounds (including persistent organic pollutants and GHGs), which are transported widely in the atmosphere, and from the atmosphere to land and water bodies (see Figure 4.4). For example, nitrous oxide (N_2O), a common atmospheric GHG, or persistent organic pollutants such

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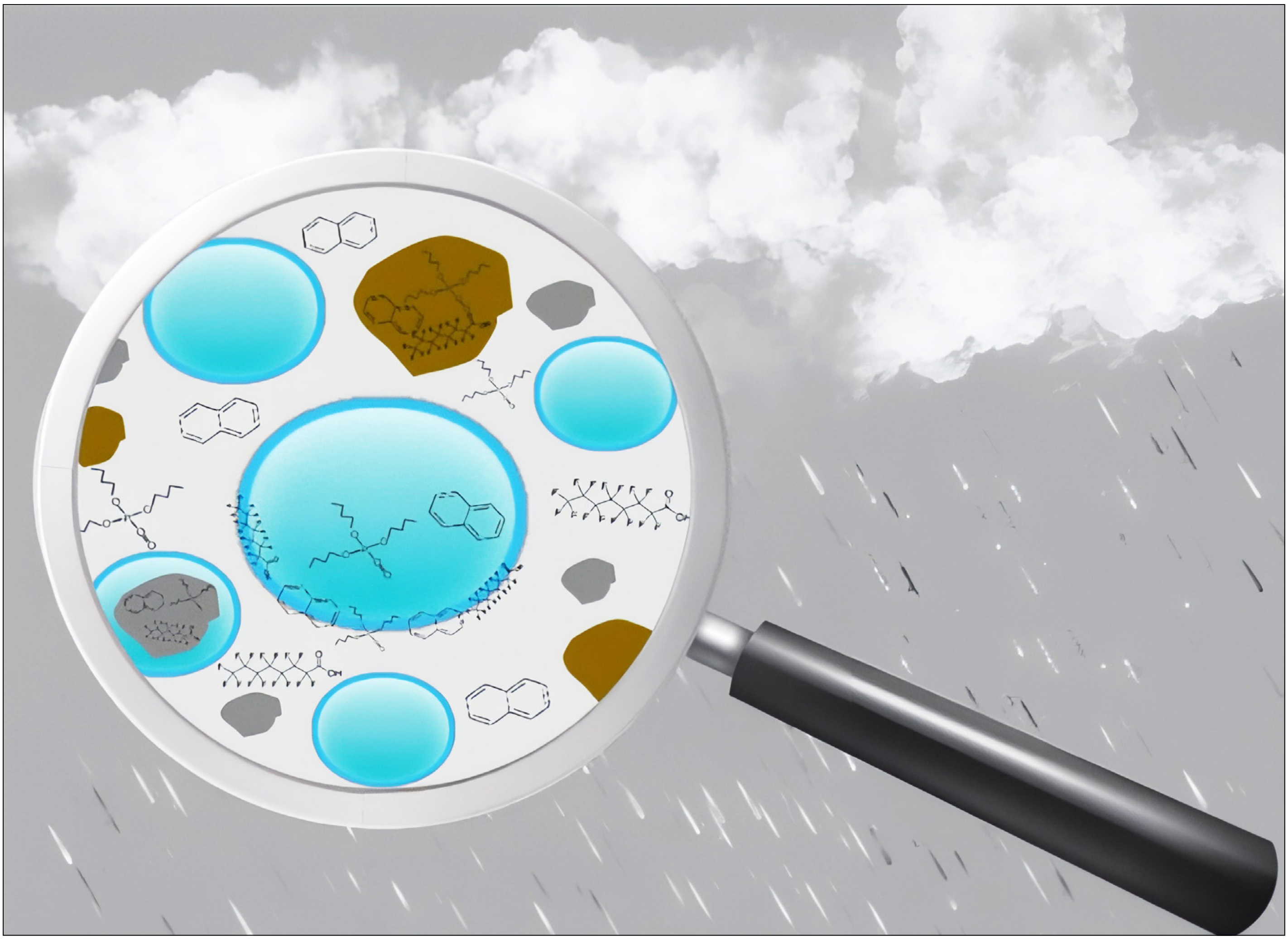
[82] https://zerowasteeurope.eu/

[83] Mechanisms through which a human activity negatively influences any part of the ecosystem

[84] https://floodlist.com/

[85] https://experience.arcgis.com/experience/5f6596de6c4445a58aec956532b9813d

[86] Phenoxy herbicides are a class of acidic herbicides that are difficult to extract from aqueous matrices.



Credit: Casas *et al.* (2021), CC-BY 4.0

Figure 4.4 Atmospheric deposition, where e.g. precipitation and particles move from the atmosphere to the Earth surface, and rain amplification of persistent organic pollutants

as PFAS, organophosphate esters (OPEs) and polycyclic aromatic hydrocarbons (PAHs), are dispersed by rainfall, accumulating in soil far from the original emission site (Casas *et al.,* 2021). As PFAS, OPEs and PAHs are listed as substances of very high concern[87], it is important to understand to what extent their environmental concentrations are a threat to organisms and humans. Considering that rainfall is increasing in high latitudes as a direct consequence of climate change, assessing and restricting the dispersal of nutrients, persistent organic pollutants and trace metals to the environment is vitally important. Risk assessments for climate change-related effects, such as of the spread of contaminants, nutrients and pathogens, should be considered in future climate action strategies, alongside forecasting of extreme weather events, to create the measures and indices necessary to deal with climate change-associated impacts (Prein *et al.,* 2017).

4.4.2 Multiple impacts of plastic pollution in the Ocean

Excessive consumption by an increasing human population, combined with inefficient global solid waste management, have transformed plastics into a pressing environmental problem. Rivers, atmospheric transport and transitional water systems have been identified as principal pathways of plastic pollution to the Ocean, where 171 trillion floating plastic pieces are estimated to have accumulated (Eriksen *et al.,* 2023). Once in the environment, plastics degrade and fragment into microplastics[88] (Sørensen *et al.,* 2021). Water basins (e.g. the Mediterranean Sea) and Ocean sinks (e.g. the North Atlantic gyre) accumulate plastics in circular currents, where they continue to degrade over time. The smaller the particle, the larger the environmental and human health consequences, as microplastics are known to have both lethal and sub-lethal effects (WHO, 2022). The leaching of toxic additives and non-intentionally added substances (NIAS; e.g. residual production chemicals) from plastics and microplastics into the surrounding environment, and the impacts this could have on marine organisms and commercially important marine species for human consumption, are emerging concerns (Focardi *et al.,* 2022). The fragmentation of plastic litter increases the surface area of the material and thereby increases the release of additive chemicals and NIAS into the surrounding environment. Pathogens, which can accumulate in the plastisphere (i.e. the biofilm that grows on the surface of the plastic), may

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[87] https://echa.europa.eu/candidate-list-table

[88] There is no current consensus on the definition for 'microplastics', despite efforts of academic, governmental, non-governmental organisations and standardisation bodies to reach one. Microplastics are generally recognised as plastic items smaller than five millimetres to a minimum limit of one micrometre (1,000 times smaller than a millimetre) (Frias and Nash, 2019)

also represent a concern (Slama *et al.,* 2021), as plastics in the marine environment have been proposed as a possible driver of antimicrobial resistance when colonised by pathogens (Kaur *et al.,* 2022) (see Figure 4.5).

Of the 350,000 chemicals registered for chemical production (Muir *et al.,* 2023), about 13,000 are used during the plastic manufacturing processes, approximately 3,200 of which have known and documented hazardous effects. In addition, only 1% of the chemicals used globally in plastic production are regulated (United Nations Environment Programme and Secretariat of the Basel, Rotterdam and Stockholm Conventions, 2023). Furthermore, a 2024 PlastChem project report synthesises the evidence on more than 16,000 chemicals potentially used or present in plastic materials and products, and notes that more than 4,200 plastic chemicals are of concern because they are persistent, bioaccumulative, mobile, and/or toxic (Wagner *et al.,* 2024). It is therefore of vital importance to incorporate safe circular economy models that do not leach unregulated substances into rivers and the Ocean. Given the complexity and the associated socio-economic and environmental consequences of this problem (Ten Brink *et al.,* 2009), a multi-stakeholder approach is needed that focuses on setting global production caps, mitigating accumulation of plastics, retrieving microplastics and microbeads from global markets, and minimising the effects on aquatic species and human health (Huang *et al.,* 2021). The UN Legally Binding Treaty for Plastics (UNEP/EA.5/Res.14, 2021) has the potential to be a policy game-changer to positively influence decision-making through feasible solutions. However, for the Treaty to be effective, strong political will is needed and industries need to be part of a much-needed systemic change.

In addition to managing the European plastics problem, Europe also has a role to play in ensuring that it does not effectively 'export its problems' by exporting its plastic waste to countries that do not have adequate waste management infrastructures, exacerbating the global problem.

Microplastics can both absorb and adsorb[89] persistent organic pollutants, such as PCBs and PAHs, and metals such as arsenic, mercury and lead (see Figure 4.5) (Frias, 2020). In nature, persistent organic pollutants and trace metals degrade very slowly, and accumulate on microplastics and sometimes subsequently in aquatic organisms via ingestion (Wang *et al.,*

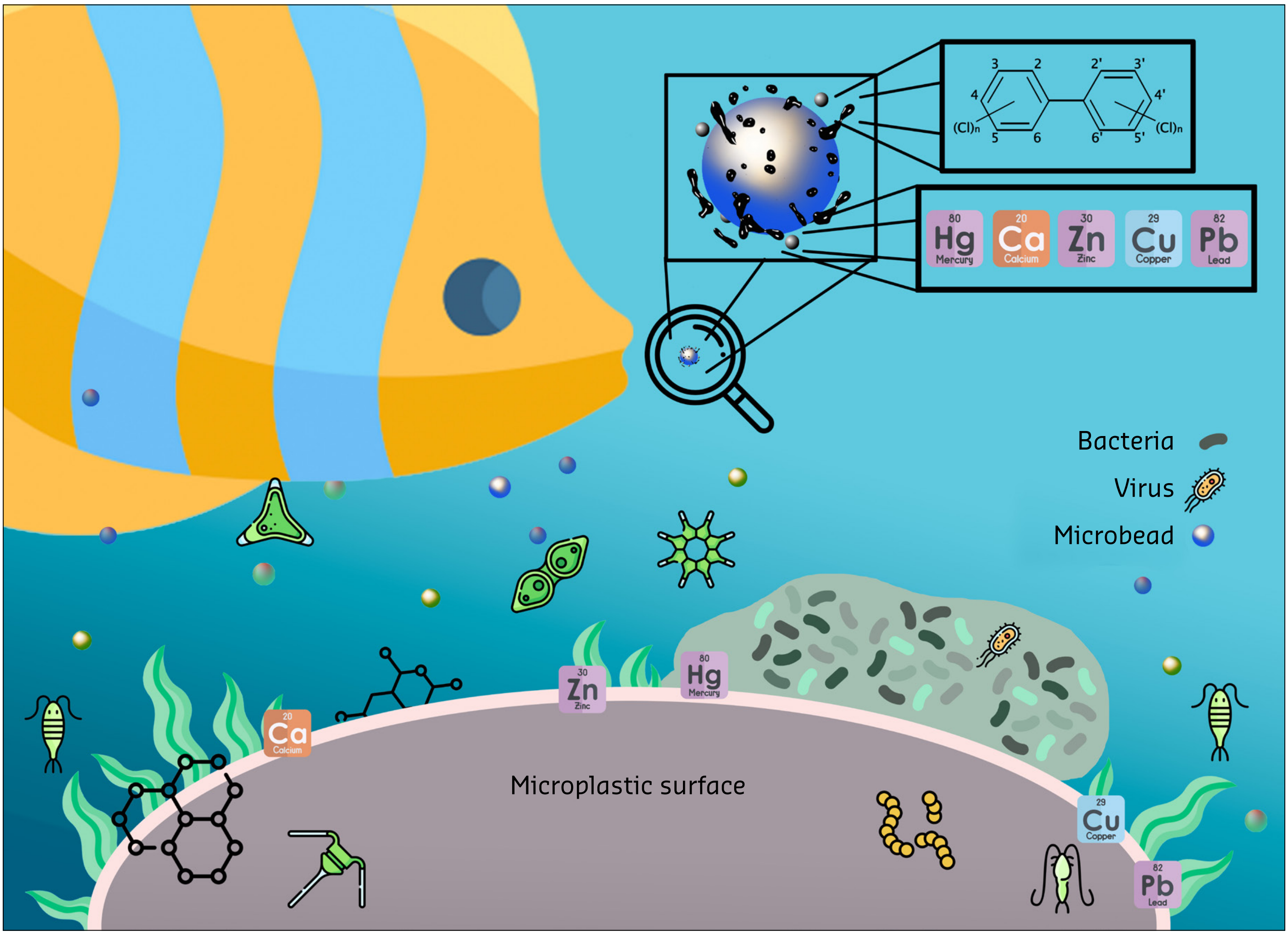

Figure 4.5 Bioaccumulation of organic and inorganic substances to the plastisphere in marine plastics

Credit: Joao Frias

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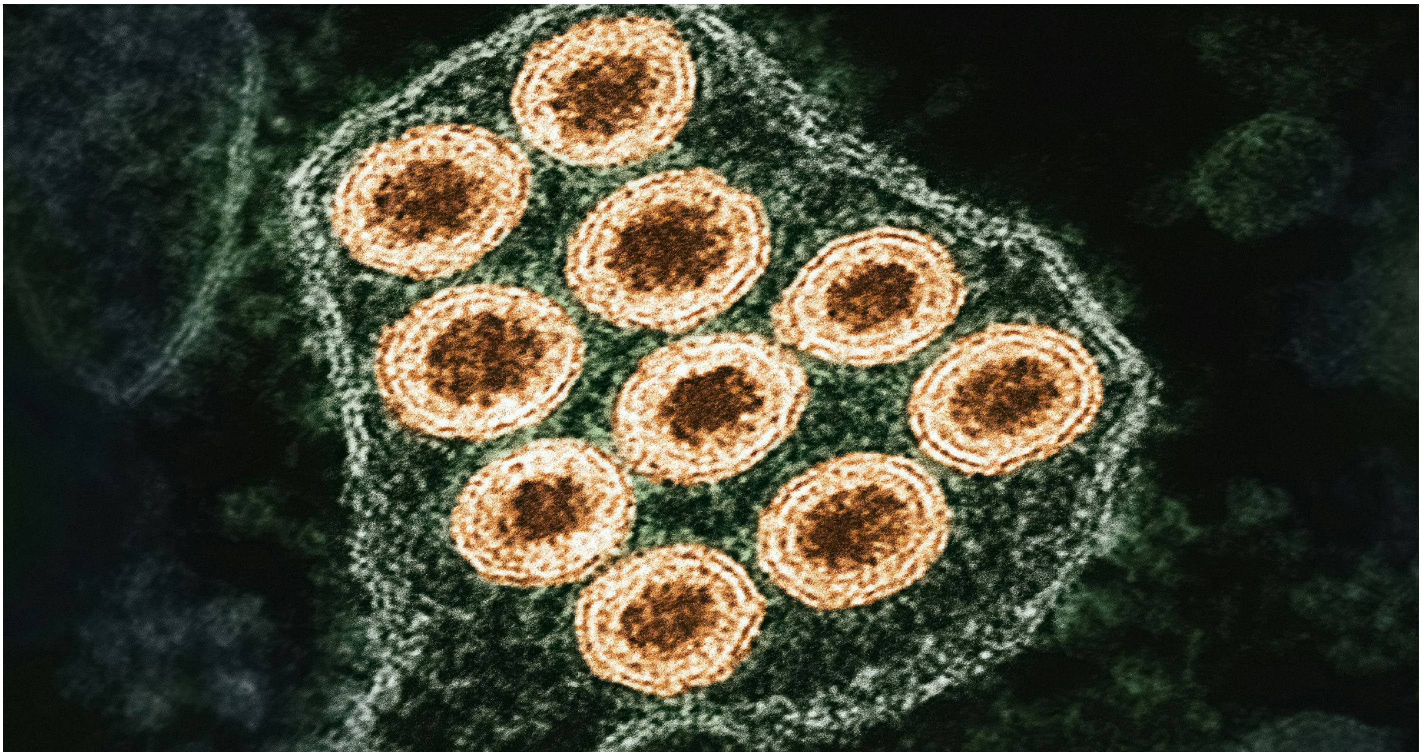
[89] Adsorption is the attraction of molecules onto the surface of a solid.

2021). Bioaccumulation and biomagnification of absorbed and adsorbed pollutants introduced from microplastics are not yet fully understood, particularly in terms of the human and environmental health impacts (Miller *et al.,* 2020). Simultaneously, biofilms growing around microplastics, or the plastisphere, provide an additional substrate for bacteria and viruses to grow. Some of these bacteria and viruses are pathogenic to human health. Given their lightweight properties and ability to travel large distances carried by currents, winds, or other organisms, microplastics act as a vector for trace metals, organic pollutants, and potential invasive species, which can spread disease in the aquatic environment.

4.4.3 Frozen pandemics and warm epidemics

The impacts of human-induced climate change, particularly global warming, on sensitive ecosystems (e.g. glaciers and wetlands) have been evident in recent years. Ice sheet and permafrost melting at current rates can potentially unlock past viral and prion[90] diseases, with unknown consequences (Lemieux *et al.,* 2022). Although the risk of transmission is considered low, examples of phytoplankton blooms (Santos *et al.,* 2022) and increased viral loads (e.g. Cholera, *Vibrio* spp.) in polar regions (Marcoleta *et al.,* 2022) raise concerns about biological 'hitchhikers' finding pathways of transmission to humans. The plastisphere can host *Vibrio* viruses (Pedrotti *et al.,* 2022) and potentially transport them across vast areas. The plastisphere and its biological diversity survives because it is surrounded by water, which provides the right conditions for these pathogens to thrive. In dry and warm inland areas however, the combination of human activities, climate change and the water cycle also play an important role in the rise of new epidemic outbreaks such as rabies (*Lyssavirus* spp.) (Nahata *et al.,* 2021), or dysentery (Wu *et al.,* 2020). Deforestation, droughts and seasonal fluctuations (e.g. El Niño Southern Oscillation) affect humidity and water quality, which can lead to the proliferation of diseases (Wu *et al.,* 2020). Preventing the spread of diseases locked in the permafrost or inland are different dimensions of the same problem, which need to be addressed through monitoring, wastewater management, and early identification and assessment of specific biochemical and/or genetic biomarkers in the water. The latter is particularly relevant for allowing the identification of viruses, bacteria, or other pathogens of potential concern to help minimise risks (Carratalà & Joost, 2019).

In conclusion, human activities produce a multitude of stressors on aquatic ecosystems, which will continue to affect future generations. Changes in European average rainfall due to climate change will lead to extreme flooding and those waters carry plastics, nutrients, legacy and emerging contaminants, and potentially disease-spreading pathogens across vast geographical areas and large distances. There are already more than 170 trillion plastic items in the Ocean, many of which have accumulated in oceanic gyres, and plastics serve as a vector for transmission of toxicants and potentially pathogenic organisms. In addition, only 1% of the approximately 350,000 chemicals used in plastic production are regulated. Ensuring high-quality data collection and policy design will require consensus on definitions, metrics and indicators. Research needs to focus on ecotoxicology and risk assessment of chemical additives and their impacts to human and ecosystem health. Permafrost melting due to global warming can unlock viral and prion diseases, and increase pathogen concentrations, thus we need to monitor biochemical and genetic markers[91] to prevent the spread of disease. Legacy and emerging contaminants might have synergistic or antagonistic effects which still need to be assessed.



Credit: National Institute of Allergy and Infectious Diseases. https://www.flickr.com/photos/niaid/53289652877/

Rabies Virus Colourised transmission electron micrograph of rabies virus particles (orange).

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[90] Prions are misfolded proteins that can transmit untreatable, infectious and fatal brain diseases in mammals (e.g. Bovine spongiform encephalopathy, also known as mad cow disease).

[91] Biochemical markers are molecules produced during the process of disease that can be tracked, while genetic markers are DNA sequences with a known physical location on the chromosome which can then help understand the links between a disease and the gene responsible.

4.5 Recommendations

4.5.1 Recommendations for policy and management

- Include a wider list of contaminants such as CECs, microplastics, pharmaceuticals, biochemical and genetic markers, and poorly understood discharge pathways, such as submarine groundwater discharge and melting of glaciers and permafrost, into policy frameworks, risk assessment procedures, and relevant and upcoming EU Directives;

- Develop an early-warming system that can rapidly go from management of CECs to biomonitoring and risk assessment, which can be adapted as new substances and knowledge emerges, particularly on their toxic effects; and

- Support collaborative research and science communication activities, including with the involvement of decision- and policymakers, to ensure they are aware of emerging issues such as extreme weather events and distribution of new emerging pollutants.

4.5.2 Recommendations for research and monitoring

- Conduct innovative monitoring to understand the deterioration of coastal freshwater reserves by intruding seawater, as well as the effects of submarine groundwater discharge on coastal waters to understand ongoing and future climate change impacts;

- Broaden the set of monitored parameters to enhance our understanding of the impacts of salinisation of freshwater resources, and form partnerships to enable monitoring in countries with relatively limited resources;

- Conduct research to create innovative, smart, nature-based, and cost-effective treatment technologies for emerging, remobilised and legacy pollutants and contaminants to optimise and improve removal efficiencies, while reducing the impacts on aquatic ecosystems and human exposure to hazardous substances;

- Monitor biochemical and genetic markers to prevent the spread of diseases; and

- Harmonise sampling, analytical research methods, reporting, and interpretation of data from freshwater and marine systems across disciplines to achieve a proper assessment of the state of the environment.

5

Ocean and Biodiversity

A grey sea slug amongst seaweeds Credit: ©Ben James, NatureScot

Biodiversity is the building block of all ecosystems and forms the basis of ecosystem functions and services provided to society. The Convention on Biological Diversity (CBD) defines biodiversity (a contraction of 'biological diversity') as *'the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems'* (CBD, 1992). In a wider context, biodiversity is thus the diversity and variability of living organisms at all levels of biological organisation, i.e. from molecules and genes to ecosystems, including the diversity of species in an ecosystem, but also their genetic, physiological, morphological, ecological, behavioural and functional diversity.

5.1 What is biodiversity?

Biodiversity is the foundation that determines the functions and services that an ecosystem provides. If biodiversity is radically changed, the ecosystem functions and services it delivers will change too. Thus, it is imperative that we understand the composition, functionality and potential changes of biodiversity in the Ocean. However, global assessments of marine biodiversity vary widely. Marine ecosystems are much less studied than terrestrial or freshwater systems, and there is no consensus on how many species there might be. In 2011, it was mathematically estimated that after 250 years of taxonomic classification only a small part of the Ocean biodiversity is known, and that over 90% of marine biodiversity was still undescribed (Mora *et al.,* 2011). This is particularly true for microorganisms, which make up the bulk of marine biomass (Bar-On & Milo, 2019; see Figure 5.1). Moreover, the adequacy of how marine biodiversity is documented varies widely. Species found in shallower parts of the Ocean are much better described than those in deeper areas, which is striking considering that more than half of the planet's surface is covered by marine zones deeper than 3,000m. The number of marine biodiversity records also decline further away from the coast and deeper into the Ocean (Webb *et al.,* 2010). This has induced multiple, wide-scale collaborative efforts to better map marine ecosystems and their biodiversity, starting with the Census of Marine Life (2000-2010)[92], a global network of researchers from more than 80 nations that engaged in a ten-year scientific initiative to assess and explain the diversity of the Ocean. The Census of Marine Life concluded that there may be 0.7–1 million marine species and that between one-third to two-thirds of marine species may be undescribed (Appeltans *et al.,* 2012). Subsequently, there is now an Action under the UN Decade of Ocean Science for Sustainable Development: Decade of Deep-Ocean Science (Howell *et al.,* 2021) or the Ocean Census[93], which estimates that there are 1.2 million species living in the Ocean, of which only about 240,000 species (i.e. less than one-third) have been discovered and named. In addition, a new freely available online database called KAUST Metagenome Analysis Platform (KMAP) describes more than 300 million marine gene groups of bacteria, viruses, and fungi (Laiolo *et al.,* 2024).

Biodiversity also has a functional aspect, consisting of ecological relationships between the organisms or genes, and the environments they inhabit (Cochrane *et al.,* 2016). In natural ecosystems, all living organisms are interconnected through inherently complex processes, and food webs offer conceptual and quantitative frameworks to understand the structure and function of biodiversity.

Marine biodiversity is declining (O'Hara *et al.,* 2021), mostly due to human activities, such as fishing or the emission of GHGs and their corresponding impacts, including eutrophication, biological invasions, global warming and Ocean acidification. The biodiversity loss observed worldwide affects ecosystem functioning and may cause irreversible loss of ecosystem resilience (Talukder *et al.,* 2022). Conversely, the loss of ecosystem resilience jeopardises ecosystem functions and may disrupt or halt the supply of key marine ecosystem services. These changes can be seen in the decrease in abundance of individual species, loss of habitat or changes to species distribution ranges, and in some cases (local) extinction and loss of locally adapted populations of species.

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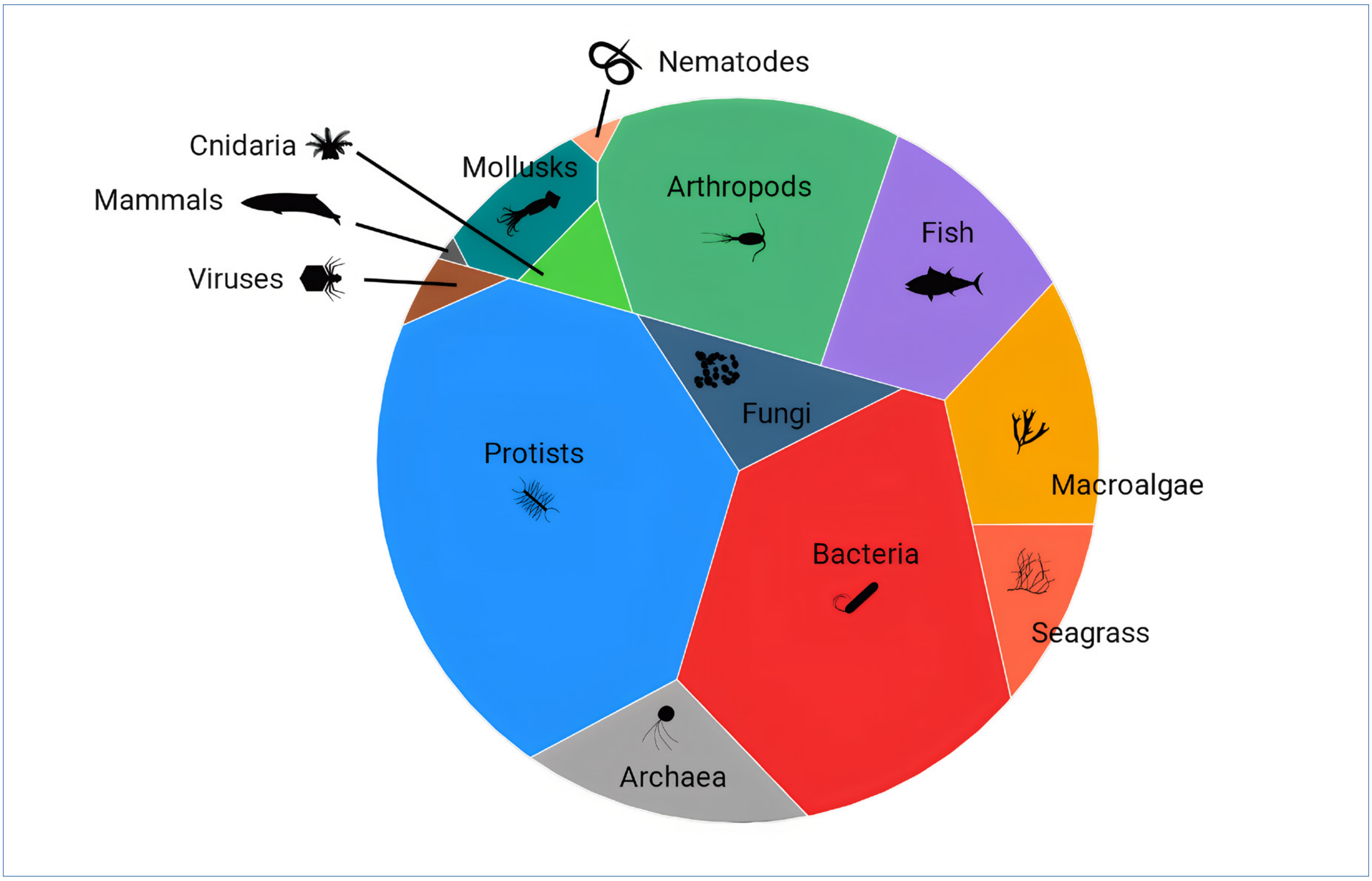
[92] http://www.coml.org/about.html

[93] https://oceancensus.org/mission/



Credit: Loïc Michel using data from Bar-On & Milo (2019)

Figure 5.1 Biomass distribution across marine taxa. It is noted that some groups are excluded either because their biomass is considered negligible and/or because there is insufficient documentation to produce a global estimate.

5.2 Biodiversity, ecosystem functioning and ecosystem services

5.2.1 Importance of biodiversity for the functioning of the Ocean

Ecosystems are tightly linked by ecological processes which transport energy and materials, primarily through biological food-webs and across species' lifecycles. For example, most primary production takes place in the few tens of metres of subsurface Ocean waters where sunlight penetrates, but this production supports life in the rest of the water column down to several thousands of metres. Conversely, upwelling of deep water adds the necessary nutrients to help support this primary production. The vertical migration of plankton, fishes and other organisms (the largest migration of life on Earth) redistributes species and nutrients in the water column daily, while seasonal migration of mobile species or plankton drifting with currents redistributes them horizontally.

An ecosystem with a mosaic of different niches[94] (such as patches of seagrass meadows, coral reefs, and bare sand), will have higher biodiversity and more ecosystem functions than a similar sized, more homogenous ecosystem. Species have different habitat preferences (also depending on their life stages), and the more habitats within a given ecosystem, the more species will be attracted. In addition, some species provide habitats for other species, i.e. reef-building corals, seagrass and large macroalgae will provide habitats for fish and invertebrates, and thereby increase biodiversity. These species are also called ecosystem engineers or foundation species because without their presence the habitat and in some cases the whole ecosystem would not exist. Species also have different lifestyles and habits thus a species-rich ecosystem will provide more ecosystem functions (Albrecht *et al.*, 2021).

Species with large populations and biomass, or that can reproduce quickly, enhance ecosystem production (i.e. how fast biomass is generated, transported and accumulated in an ecosystem). Keystone species, which can have a relatively larger impact on their environment than would be expected from their biomass, have key functions that highly influence the structure of biodiversity and therefore impact the function of the ecosystem. Examples of keystone species include predatory fishes or marine mammals which have a top-down effect by regulating the biomass of their prey, helping to maintain the biomass levels of lower trophic levels (Baum & Worm, 2009). Reducing the predatory fish population or changing its size distribution because of intense fishing pressure has significant effects on the ecosystem's function, which cascades through the food web. For example, removal of large cod (*Gadus morhua*), in coastal areas of Sweden has increased the number of small fish e.g. small gobies (Gobiidae), which feed on small crustaceans that in turn graze on the plants and plant-like organisms that grow on seagrasses, leading to overgrown and

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[94] A niche is the match of a species to a specific environmental condition.

unhealthy seagrass meadows (Moksnes *et al.,* 2008). Similarly, in an MPA in Portofino, Italy, large fish species such as amberjack (*Seriola dumerili*), groupers (*Epinephelus* spp.) and scorpionfishes (*Scorpaena* spp.) control the food web through predation and have positive top-down control effects. However, when their populations decline due to overfishing, the lack of top-down control can have cascading consequences across the ecosystem (Prato *et al.,* 2016).

Marine microorganisms play a central role in the Ocean carbon cycle as they function as a biological pump and contribute to fluxes in the global nitrogen cycle. The diversity of microorganisms is fundamental to the maintenance of every ecosystem's biogeochemical cycle (Strom, 2008). The analysis of metagenomes for signs of adaptation can serve as biosensors and highlight regional shifts that may occur in nutrient loads and plankton elementary composition (Garcia *et al.,* 2020). The stability of these cycles is vital for all marine organisms, as alterations in the populations of microorganisms can profoundly impact ecosystem functioning, thereby affecting its capacity to sustainably deliver ecosystem services.

Although the marine environment generally has no barriers, many species of fish, invertebrates and macroalgae are genetically subdivided and locally adapted to different biotic and abiotic conditions, which include temperature or salinity ranges, tidal regimes and prey preferences. For example, in Europe there are many local subpopulations of blue mussels (*Mytilus edulis*) (Śmietanka *et al.,* 2014), and the Atlantic herring (*Clupea harengus*) is subdivided into more than 20 local populations, all adapted to different biotic and abiotic conditions as well as reproductive seasons, i.e. spring or autumn spawners (Han *et al.,* 2020).

This diversity at the genetic level (called genetic biodiversity) ensures that these species have a higher capacity to evolve and adapt (Reusch *et al.,* 2005). This ability to adapt is critical for species in dealing with climate change, hence the need to protect genetic diversity (also known as the gene pool). Genetic diversity of foundation species is fundamental for ecosystems. For example, more genetically diverse seagrass meadows are more productive, host more species and are more resilient to extreme events (Reusch *et al.,* 2005). Genetic diversity requires large populations, while fragmentation and isolation of populations leads to genetic degradation.

Credit: Noz Urbina, Pexels

Scorpionfishes are examples of keystone species, which control the food web through predation and have positive top-down effects on the ecosystem.

5.2.2 Biodiversity and ecosystem services

Biodiversity determines the functions and services that the ecosystem provides, and while relationships between marine biodiversity and ecosystem functioning are complex, biodiversity influences ecological processes and could promote resilience against environmental changes (Strong *et al.,* 2015). However, our understanding of the linkages between biodiversity, ecosystem processes and services is incomplete. Further research on how ecosystem services depend on ecosystem structure (such as species and habitats), processes and functions is required to map and assess the distribution of marine ecosystem services and to pave the way for understanding their potential value (Austen *et al.,* 2019). For a more detailed discussion on ecosystem services, see Chapter 2.

5.3 Activities and stressors affecting Ocean biodiversity

Many human activities have direct or indirect impacts on the abundance and distribution of marine resources, which can have measurable effects on biodiversity (O'Hara *et al.,* 2021). With a growing human population, increased demand for resources, and new technologically advanced marine and maritime industries, our impact on the state and development of marine biodiversity is expected to increase further.

Human activities and stressors vary in time and space. Due to this variability and differences between ecosystems in their innate sensitivity to stressors, the overall magnitude of the impacts also differs. Impacts may be persistent and long-lasting, or short-term and acute. Different activities (often termed 'drivers') can cause the same stressor, and a single stressor can trigger many different ecosystem reactions. In addition, multiple stressors can interact over space and time, leading to cumulative impacts (Korpinen *et al.,* 2019). These multiple stressors have previously been highlighted in Chapter 4 of EMB Position Paper N°. 24 Navigating the Future V (European Marine Board, 2019) and within a coastal context in EMB Position Paper N°. 27 on Coastal Resilience (Villasante *et al.,* 2023).

To better understand and potentially mitigate their impact, stressors have been defined and grouped in many ways e.g. according to their source(s) or severity of impact. While some stressors may be site-specific, many have more general impacts. Three large-scale studies by the European Environment Agency (EEA; Korpinen *et al.,* 2019), the International Council for the Exploitation of the Sea (ICES, 2021) and Kvamsdal *et al.* (2023) have highlighted the most important stressors on Ocean biodiversity resulting from established human activities (Table 5.1).

Table 5.1 The most important established stressors on marine environment and biodiversity according to a) Korpinen *et al.* (2019), b) ICES (2021), and c) Kvamsdal *et al.* (2023). The list is unranked and in alphabetical order. Note that the terminology used differs somewhat between the studies, therefore the present wording has been adapted from the original sources.

STRESSORS
Chemical contamination/pollution [a,b,c]
Climate change (global warming, acidification, sea-level rise) [a,b, c]
Damage to seabed habitats (abrasion and extraction of non-living resources) [a,b,c]
Introduction of non-indigenous (invasive) species [a,b,c]
Marine litter, including plastics [a,b,c]
Nutrient and organic enrichment / eutrophication / deoxygenation [a,b,c]
Overexploitation of fish and shellfish stocks [a,b,c]
Underwater noise [a,c]

While there is consensus about the main known direct stressors on marine biodiversity, understanding the importance of new and future stressors is more difficult. Herbert-Read *et al.* (2022) brought together a team of 30 transdisciplinary scientists, policymakers and practitioners to study 75 possible emerging issues that could have both positive and negative impacts on marine and coastal ecosystems. They agreed on 15 topics, grouped according to ecosystem impacts, resource exploitation and new technologies (Table 5.2). This table is supplemented by additional issues highlighted in a similar horizon scan exercise by Sutherland *et al.* (2023), which directly relate to or may influence marine biodiversity, either positively or negatively.

Table 5.2 Emerging issues which can either positively and/or negatively affect the marine environment and biodiversity by a) Herbert-Read *et al.* (2022) and b) Sutherland *et al.* (2023)

EMERGING ISSUES	
Ecosystem impacts	Wildfire impacts on coastal and marine ecosystems [a]
	Coastal darkening due to increased suspended particles in the water, reducing light penetration [a]
	Increased toxicity of metal pollution due to Ocean acidification [a]
	Equatorial marine biodiversity declining due to climate migration [a]
	Effects of altered nutritional content of fish due to climate change [a]
	Accelerating upper Ocean currents causing increased stratification (and affecting the biological carbon pump among others) [b]
	Potential side effects of Ocean garbage patches, which host distinct ecosystems, presenting challenges for remediation [b]
	Diminished long-term resilience of coastal wetlands due to sea-level rise [b]
Resource exploitation	The untapped potential of the extraction of marine collagens and subsequent impacts on marine ecosystems [a]
	Impacts of expanding trade for (target and non-target) fish swim bladders[95] [a]
	Impacts of fishing for mesopelagic[96] species on the biological Ocean carbon pump [a]
	Extraction of lithium from deep-sea brine pools [a]
	Artificial-light fisheries at greater depths with unknown ecological effects [b]
	Increased demand for chitosan[97] increasing incentives for expansion of coastal aquaculture, increasing risks to coastal and nearshore ecosystems [b]
New technologies and policies	Co-location of marine activities [a]
	Floating marine cities [a]
	Trace-element contamination compounded by the global transition to green technologies [a]
	New underwater tracking systems to study non-surfacing marine animals [a]
	Soft robotics for marine research [a]
	The effects of new biodegradable materials in the marine environment [a]
	Reduced inorganic fertiliser use via custom-designed microbes and plants which could reduce eutrophication [b]
	Microbiome stewardship for conservation i.e. manipulating the marine microbiome to enhance resistance to coral bleaching [b]
	Reporting and prioritisation of biodiversity impacts by private actors and in legislation such as the EU Nature Restoration Law [b]
	Accelerated use of machine learning to design and screen for possible drugs to create novel therapeutics and toxins [b]

5.4 Biological invasions as an increasing concern

The CBD defines invasive alien species as *"plants, animals, pathogens and other organisms that are non-native to an ecosystem, and which may cause economic or environmental harm or adversely affect human health"*[98]. The number of settled invasive alien species is growing exponentially (Mormul *et al.*, 2022). For marine species this is primarily due to increased maritime traffic, aquaculture, and trans-oceanic canals, which act as vectors. European seas harbour 1,400 alien species, 80% of which were introduced after 1950 (EEA, 2017) (Figure 5.2). This massive arrival is part of a global phenomenon and is addressed in national, European, and international policies, which try to prevent the arrival and spread of such species (e.g. MSFD, EU Regulation on invasive alien species (Regulation 1143/2014, 2014), Aichi Biodiversity Target 9[99]).

Invasive alien species are a significant and growing part of many marine ecosystems. For instance, the Mediterranean Sea is a hotspot for invasions with 800-1,000 invasive alien species, i.e. equivalent to 5% of its total native species and 69% of the EU's marine invasive alien species. This is an increase of 204% between 1970 and 2013 (EEA, 2017). Climate change allows invasive species from warmer latitudes to colonise new areas, expanding their impact in European waters. This is especially true for

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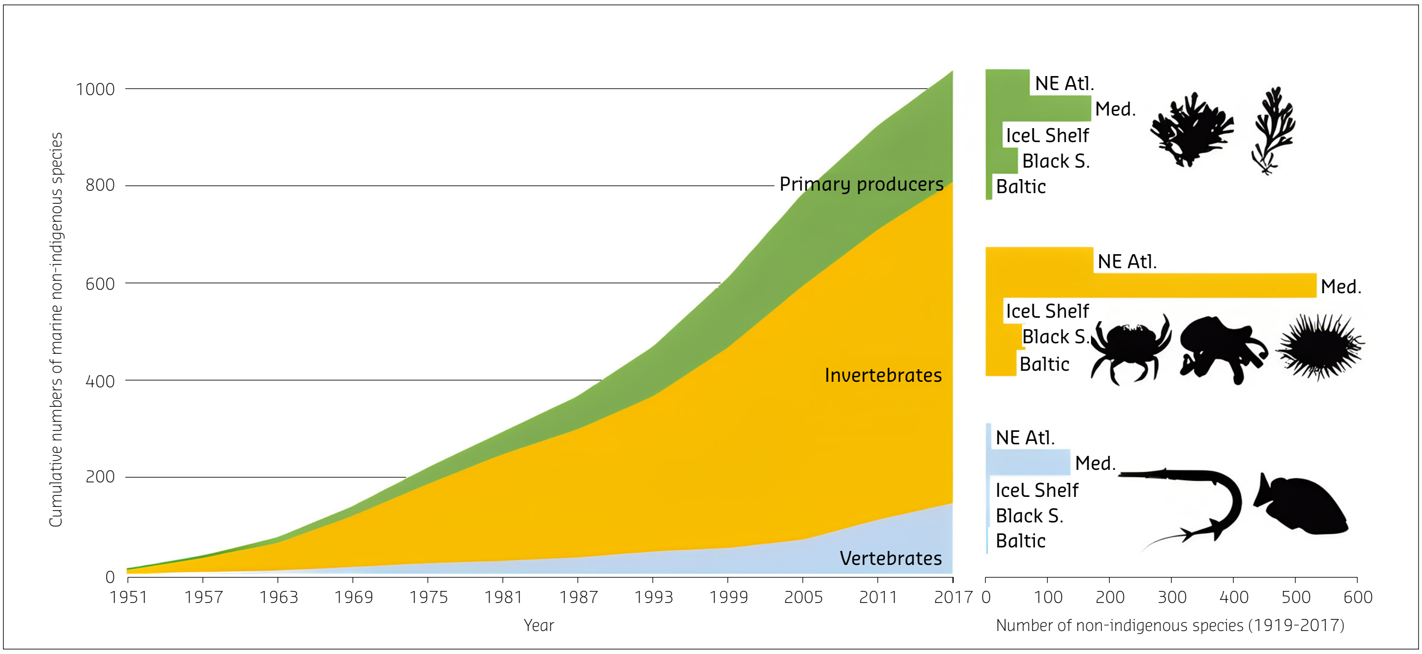
[95] A swim bladder is an internal gas-filled organ that helps some fish species to control their buoyancy.

[96] The mesopelagic zone, also called the twilight zone as sunlight can still be detected there, is typically taken to be between around 200-1,000m depth.

[97] Chitosan comes from shellfish exoskeletons and is used in the manufacture of medication.

[98] https://www.cbd.int/idb/2009/about/what/

[99] https://www.cbd.int/aichi-targets/target/9



Credit: Christophe Lejeusne using data from EEA[100]

Figure 5.2 Number of marine invasive alien species per functional group introduced in European seas (EU and non-EU) over the period 1949-2017: temporal trend (left) and global repartition per regional seas (right). NE Atl.=North-East Atlantic; Med.=Mediterranean Sea; IceL. Shelf=Icelandic shelf; Black S.=Black Sea; Baltic=Baltic Sea. Data are aggregated per six years.

Lessepsian species such as the blue crab (*Portunus segnis*) which were introduced through the Suez Canal and are now expanding westwards and disturbing ecosystems by competing with local species for food and habitat, causing economic damage and threatening fisheries and aquaculture. The arrival of invasive species has an added impact as they can carry microorganisms, viruses and/or parasites that native species have not previously been exposed to, which can go unnoticed in the short-term and only be detected later when they have devastated ecosystems. Thus, there is a need for a scientific and legal cooperative network for all bordering countries around various sea basins that could monitor the spread of these invasive alien species in cooperation with non-EU countries.

In highly human-modified ecosystems with poor water quality and significant artificial habitats such as ports and marinas, invasive alien species can represent 15-30% of all species on average, and up to 75% in benthic communities (Tamburini *et al.,* 2021). Coastal urbanisation, i.e. the creation of ports, shoreline protection and offshore renewable energy installations, create coastal and offshore artificial habitats that help these invasive species to disperse and settle, thereby altering ecological connectivity that could significantly impact marine biodiversity. Despite its extent and prominence, the consequences of this so-called 'Ocean sprawl' remain poorly studied (Todd *et al.,* 2019). The levels of risk for invasive species associated with Ocean sprawl should be documented and evaluated by a competent independent authority prior to the establishment of artificial infrastructures in coastal areas.

Invasive alien species have a huge impact on ecosystems including terrestrial, freshwater, and marine, and may cause population or species extinctions, as well as wider disruptions at the biological community and ecosystem levels (Anton *et al.,* 2019). Some of these impacts can translate into large economic losses, with one study estimating total reported costs (including expenditure on eradication as well as economic losses) of invasions of US $ 1.288 trillion (in 2017) over 1970–2017 (Diagne *et al.,* 2021). Invasive species can also negatively impact human health, such as via intoxication or death from poisonous species. Examples include the silverstripe blaasop (*Lagocephalus sceleratus*), a type of puffer fish, and venomous species such as the reef stonefish (*Synanceia verrucosa*) (Mazza & Tricarico, 2018). Their ecological effects are less obvious as we move offshore. Some marine alien species do not have significant ecological impacts so they could be considered harmless or even beneficial (Zwerschke *et al.,* 2016), although their effects might not be readily noticeable. Conversely, some invasive species could cause population extinctions, as invasive lionfishes (*Pterois* spp.) have done on coral reef fishes. The ecological and evolutionary mechanisms behind the success of invasive species are diverse and may occur at any time during the invasion process (Daly *et al.,* 2023), thus they require further study, as do the epidemiological, genetic and ecological consequences for native species and ecosystems.

Invasive alien species represent a situation of 'ecological roulette' (Cariton & Geller, 1993), where an invasive species can cause significant ecological and economic impacts but can also represent economic opportunities. One example is the red king crab (*Paralithodes camtschaticus*) which was introduced into the Russian part of the Barents Sea in the 1960s and has now become an important fishery in Russia and Norway, although the economic benefits might be negated by the impact this species has on the ecosystem and local fisheries (Kourantidou & Kaiser, 2019). The justification to introduce species, or not to take steps to eradicate invasive species, in the hope of gaining economic benefits may be biased by a lack of information on possible negative impacts. For example, the blue crab (*Portunus segnis*) induced a rapid collapse of local fisheries in Tunisia with deep socio-economic impacts before the fishery adapted and could start

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[100] https://www.eea.europa.eu/data-and-maps/indicators/trends-in-marine-alien-species-mas-3/assessment

exploiting it (Marchessaux *et al.,* 2023). This species' recent spread in the EU has not yet had a significant socio-economic impact. However, there is also a risk of a strong negative impact on EU fisheries in the near future.

Management of marine invasive alien species is challenging. Very few successful eradications have been reported, while failed management strategies abound (Simberloff, 2021). Even though novel management approaches require further studies, current marine invasive species should be contained, and we should prevent the arrival of new invasive alien species through public awareness-raising, the adoption and implementation of management measures such as the Ballast Water Management Convention for ships (IMO, 2018), and by finding commercial uses for invasive species (Giakoumi *et al.,* 2019). We should also effectively understand and, where possible, manage factors that enhance bio-invasions, such as urbanisation, 'Ocean sprawl' and pollution (Johnston *et al.,* 2017).

Credit: L. Haddock, U.S. Fish and Wildlife Service

Catching a red king crab, an invasive species in the Barents Sea.

5.5 Changes in species distributions

Climate change is becoming a major threat to marine biodiversity, especially because it increases sea temperatures and causes marine heatwaves (see Section 3.3.1). Climate change is altering the biotic and abiotic properties of marine habitats, which alters the composition of species that can survive and reproduce there, thus changing the biodiversity of the ecosystem. Most organisms are vulnerable to warming due to their physiology, which defines how sensitive they are to temperature. In addition, sessile species have a limited ability to move or propagate to alternative locations with more adequate temperatures. Comparison of biota across land and the Ocean suggests that marine species generally inhabit environments closer to their upper temperature limits, which may at least partly explain the substantially higher rate of local extinctions related to warming in the sea relative to warming on land (Pinsky *et al.,* 2019). The frequency and severity of future impacts will differ in space and depend on global emission trajectories (IPCC, 2019). Significant decreases in marine productivity and biodiversity are anticipated towards 2100, especially in some more vulnerable ecosystems, such as the enclosed Baltic Sea and the shallow North Sea. The detrimental effects are expected to be lower in low emission scenarios, corresponding roughly to a global atmospheric temperature increase of 1.5-2°C by 2100, than high emission scenarios, corresponding to temperature increases of 3.6-4.4°C (IPCC, 2019). For example, Sandø *et al.* (2022) show clear differences in consequences for fish species relating to different climate scenarios.

In response to temperatures increasing beyond their average range, organisms must adapt. Large populations that contain a lot of genetic variation in the traits that need to change (Kawecki & Ebert, 2004), or species that can change their behaviour to survive in a changing environment (Sih *et al.,* 2011) will have the highest capacity to adapt. To reduce climate-induced physiological stress, individuals and populations can move into deeper, colder waters, or move to higher latitudes (i.e. further away from the equator). Among other groups, phytoplankton, kelp, fishes, marine mammals and seabirds have all already shown such temperature related shifts in distribution (IPCC, 2019).

If a population cannot adapt to the new conditions, or expand its range into a more suitable area, it could become extinct. A population's adaptive potential to respond to climate change and thrive under changing environmental conditions relies on its genetic diversity (Sgrò *et al.,* 2011). In the Ocean, species are often widely distributed but are subdivided into genetically different, locally adapted populations. However, local populations of common species with specific adaptations, such as being more temperature tolerant, are already shrinking and being lost due to a focus on species management rather than population management. Examples include local fjord populations of cod in the North Atlantic, which have historically been managed as part of a large single stock but are now reported to consist of genetically distinct populations (Morris & Green, 2021). In transitional environments, such as the Baltic Sea, that have large temperature and salinity variations, populations of foundation species of seagrass and seaweeds, and species of predatory fish, are adapted to these environments and have become relatively isolated from other populations (Johannesson *et al.,* 2020). Isolation increases their risk of extinction, as breeding with other populations of the same species is no longer possible because of the adaptation to a marginal environment and the isolation from central populations (Johannesson *et al.,* 2011).

Changes in the ranges of species have implications that are often overlooked. When species move to new habitats, they might spread microorganisms that could be detrimental to the native species that occupy the new habitat. These species might be severely affected by these new pathogens and suffer an epidemic (e.g. as was the case with the parasite-driven collapse of the Mediterranean pen shell, *Pinna nobilisa*) (Anton *et al.,* 2019). Conversely, the species that moved may also be susceptible to pathogens in the new ecosystem and suffer epidemic events themselves. Therefore, it is necessary to have a map of the different pathogenic microorganisms (i.e. a spatio-temporal epidemiological map) that can be used to predict future epidemic risks in the Ocean.

Temperature increase and retreating sea-ice have significant implications for Arctic and sub-Arctic marine ecosystems. For example, in the Barents Sea, temperature increase has increased cod abundance, but negatively affected the smaller Arctic fish species resident in the Northern Barents Sea (Fossheim *et al.,* 2015). In the future, with sea-ice predicted to retract permanently, gross primary and secondary production will increase, and this new state of sub-Arctic ecosystems is expected to become permanent. By comparison, cod in the North Sea are declining while other species are occupying their niche, such the European hake (*Merluccius merluccius*), a warm-temperate species, and the temperate salmon lice cleaning wrasses (Labridae) (Knutsen *et al.,* 2013). These changes will likely have significant impacts on the biological communities of these ecosystems. For instance, hake is a voracious predator and has a much larger trophic impact than cod and will likely have a larger top-down trophic effect on the food webs that could ultimately affect the biodiversity of the ecosystem (Cormon *et al.,* 2016).

Climate change-induced habitat changes are by no means restricted to fish. Global distributions of seaweed are changing in response to changing climate and other human impacts (Duarte *et al.,* 2022). Model predictions show that kelp forests will disappear at the warm end of their distribution and expand poleward and that this will happen faster in high emission scenarios. Kelp forests provide habitat for many juveniles of demersal and pelagic fish species (Lebrun *et al.,* 2022), therefore these changes affecting foundation species will have huge implications for the biodiversity of the ecosystem.

Global warming-induced variation in spatial distribution and abundance of fish stocks has already challenged the management of important fisheries. For example, the stock size of North-East Atlantic mackerel (*Scomber scombrus*) in the Nordic Seas increased significantly from 2007-2016. During this period of regional Ocean warming, their summer feeding shifted westward by 1650km and northward by 400km (Olafsdottir *et al.,* 2019). The resulting expansion into Icelandic and Greenland waters was totally unexpected and highly challenging to the regional multilateral management system.

Although mackerel have since returned to their normal distribution, their range is projected to expand further into Greenland's waters under both the moderate (RCP 4.5) and the extreme (RCP 8.5) IPCC emissions scenarios (Jansen *et al.,* 2016), making conflicts more likely in the future (Spijkers *et al.,* 2021). This and other examples cause concern that the effectiveness of Ocean and fisheries governance and management to achieve mandated ecological, economic and social objectives will be reduced by climate change. Climate-induced changes in distributions of commercial fishes, currently managed in specific areas based on established distribution patterns, will increase the risk of conflicts between countries, e.g. see the cod (Steinsson, 2016) and mackerel (Gray, 2021) wars. It will also increase conflicts among fishers, and between fishers and authorities. These risks are especially widespread under high emissions scenarios and highlight the limits of established natural resource management frameworks for managing ecosystems under climate change (Villasante *et al.,* 2023). As also recommended in Chapter 2, we need to understand the nature of these conflicts and their drivers, and deploy appropriate means to address them, including via policy and diplomatic approaches and working with all relevant stakeholders, to avoid escalation.

Credit: ©Alasdair O'Dell, SAMS, CC BY-NC 2.0

Kelp forest off the Isle of Seil, Scotland

5.6 Biodiversity conservation and restoration

5.6.1 A baseline for marine biodiversity

As discussed above, understanding how marine biodiversity is changing and how this will affect ecosystem functions and/or services is crucial. Biodiversity is highly variable in space and time, and referring to historical baselines will become increasingly unrealistic. In addition, Shifting Baseline Syndrome[101] leads to underestimation of past biodiversity and how it has changed over time (Soga & Gaston, 2018). We therefore need a way to establish representative baselines that can be used to identify targets for management, conservation and restoration. This will also be crucial to comply with the requirements of the EU Nature Restoration Law to restore specific habitats of the marine environment (Regulation 2024/1991, 2024).

There are several ways in which reliable baselines for ecosystems can be developed. Reference ecosystems can be used as reference states to characterise the condition of ecosystems with no direct human degradation (although climate change impacts all ecosystems). This is not necessarily the same as the historic state, as reference ecosystems also account for the capacity to change in response to changing conditions. In this regard, the Evaluation of Population Change assessment proposed by Rodrigues *et al.* (2019) uses species' occurrence or spatial abundance over multiple generations in areas of lower impact to estimate what the current population size would be in areas that have been heavily impacted. An alternative is the use of temporal baselines (Borja *et al.,* 2012), meaning that the reference corresponds to what has been observed in a selected area for a given time-period. It is possible to quantify future changes against past changes and interpret how much biodiversity has been gained, lost or in what way it has been modified. However, it is important to note that available biodiversity monitoring data do not date back far enough in time and thus are unlikely to reflect the full impact of anthropogenic pressures (Mihoub *et al.,* 2017).

5.6.2 Conservation and management

Conservation efforts, and the management approaches adopted to achieve such efforts, are used to conserve marine biodiversity in its current state. Understanding current biodiversity, including species, genetic, taxonomic and functional diversity, is crucial for informing successful conservation efforts (Lotze, 2021). Many

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[101] Shifting Baseline Syndrome is a gradual change in the accepted norms for the condition of the natural environment due to a lack of experience, memory and/or knowledge of its past condition.

traditional conservation and management approaches either focus on input controls, i.e. those that control or restrict damaging or disruptive activities in marine space both temporally or spatially, or output controls, i.e. those that control quantities of species that can be extracted from an area (Bellido *et al.,* 2020). Approaches that can be applied to conserve all components of biodiversity must be identified. This may involve moving away from traditional conservation measures focused on protecting individual threatened species and looking towards the conservation of whole ecosystems.

A key issue in conserving and managing biodiversity is addressing unsustainable human practices and stressors (see Section 5.3). Overfishing and climate change represent the greatest stressors for marine environments and the greatest threats to biodiversity (IPBES, 2019). In terms of fisheries, conserving biodiversity requires innovative management, including ecosystem-based management, and where appropriate, MSP (see Section 2.4 for more details). Single-species fisheries management based on maximum sustainable yield (MSY) ignores the genetic and size structure of populations and the connected nature of ecosystems, and hence the conservation of biodiversity. Ecosystem-based fisheries management has therefore been identified as a necessary approach and is enshrined in European and global law (Rodriguez-Perez *et al.,* 2023), as it is one of the most effective measures to promote the conservation of the marine environment. However, it is still to be implemented in fisheries policies. Fishing must also be managed alongside numerous other activities including shipping, recreation and offshore energy extraction, which requires information on the impacts of these emerging and expanding activities on marine biodiversity.

MPAs prioritise the conservation of nature and are area-based management tools that policymakers, managers and local communities use to stop the loss of biodiversity, the disruption of Ocean ecosystems, and the decline of the benefits that healthy Ocean ecosystems provide to people (Grorud-Colvert *et al.,* 2021). According to Protected Planet[102], at the time of writing, the global coverage of MPAs was 8.16%, and the majority of these were in national waters. The CBD target for MPAs was to protect 10% of the Ocean by 2020 (under Aichi Target 11[103], which also aligns with SDG Target 14.5). The new target under the Kunming-Montreal Global Biodiversity Framework of 2022 has elevated that target to at least 30% of the Ocean through highly or fully protected MPAs by 2030 (the ‘30 by 30’ initiative). In 2023, the UN agreed, under the United Nations Convention on the Law of the Sea (UNCLOS), on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction (ABNJ)[104], otherwise known as the UN Biodiversity Beyond National Jurisdiction (BBNJ) Treaty or High Seas Treaty. This Treaty also enables MPAs and other forms of area-based management to be established in ABNJ.

Where overfishing is the problem, MPAs can help to maintain age distribution, genetic and population diversity to support harvested fish stocks (Di Franco *et al.,* 2016). MPAs can also provide protection from many other stressors, such as extraction of aggregates and minerals, the building of offshore structures (including windfarms and other offshore renewable energy installations), light and noise pollution, and contaminants from activities such as aquaculture and mining. If appropriately designed and enforced, MPAs can aid in protecting biodiversity against these multiple stressors. MPAs are also useful for increasing overall biomass and diversity of species (Bellwood *et al.,* 2004). However, the establishment of MPAs alone does not guarantee biodiversity is conserved. They also need to be well designed and enforced. MPAs need to form ecologically coherent networks (Jonsson *et al.,* 2020) that ensure connectivity among sites. Biophysical modelling that predicts connectivity can be used to support optimal placement of new MPAs. Under climate-induced migration (see Section 5.5), the location of MPAs that can support future range shifts of species will be critical. MPAs are also not only used for marine biodiversity protection but sometime rather reflect aims of protecting an attractive coastal landscape, thus trade-offs in the placement of MPAs needs further study. If appropriately protected, MPAs can also contribute to climate mitigation, for example by protecting Blue Carbon ecosystems such as seagrass meadows and tidal marshes.

It is important to note that conservation and management need to take into consideration multiple dimensions of human activities in space and time, equity and governance are key considerations, and spatial management is just one of the many tools available to managers. Indeed, biodiversity and ecosystem functions must be maintained everywhere. Hence all marine activities, not least fisheries and aquaculture, need fit-for-purpose regulations, and development of new methods and approaches to reduce and eliminate their threats to ecosystem function and biodiversity of the ecosystem in which these activities are taking place.

5.63 Restoration

Unsustainable development of human activities can directly and indirectly accelerate deterioration of the marine environment, drastically affect biodiversity, reduce ecosystem services, and negatively impact economic prosperity and environmental sustainability. Active restoration, or the process of re-establishing a habitat’s structure and function following degradation by human activities and climate change (Elliott *et al.,* 2007), can reverse this trend. The degradation of many coastal ecosystems has triggered growing interest to adopt innovative approaches integrating restoration and conservation efforts in a holistic manner for ecosystem-based management (Abelson *et al.,* 2020). One of the targets of the recently agreed Kunming-Montreal Global Biodiversity Framework[105] is to ensure that by 2030 at least 30% of *‘degraded terrestrial, inland water, and marine and coastal ecosystems are under effective restoration’*.

Restoration is one of the three strategies to mitigate degradation and damage, along with reducing impacts and rehabilitation. Reducing impacts indirectly contributes to passive recovery (passive restoration), e.g. by removing upstream pollutants and hence improving water quality, banning human uses, and protecting coastal marine habitats by reducing, removing

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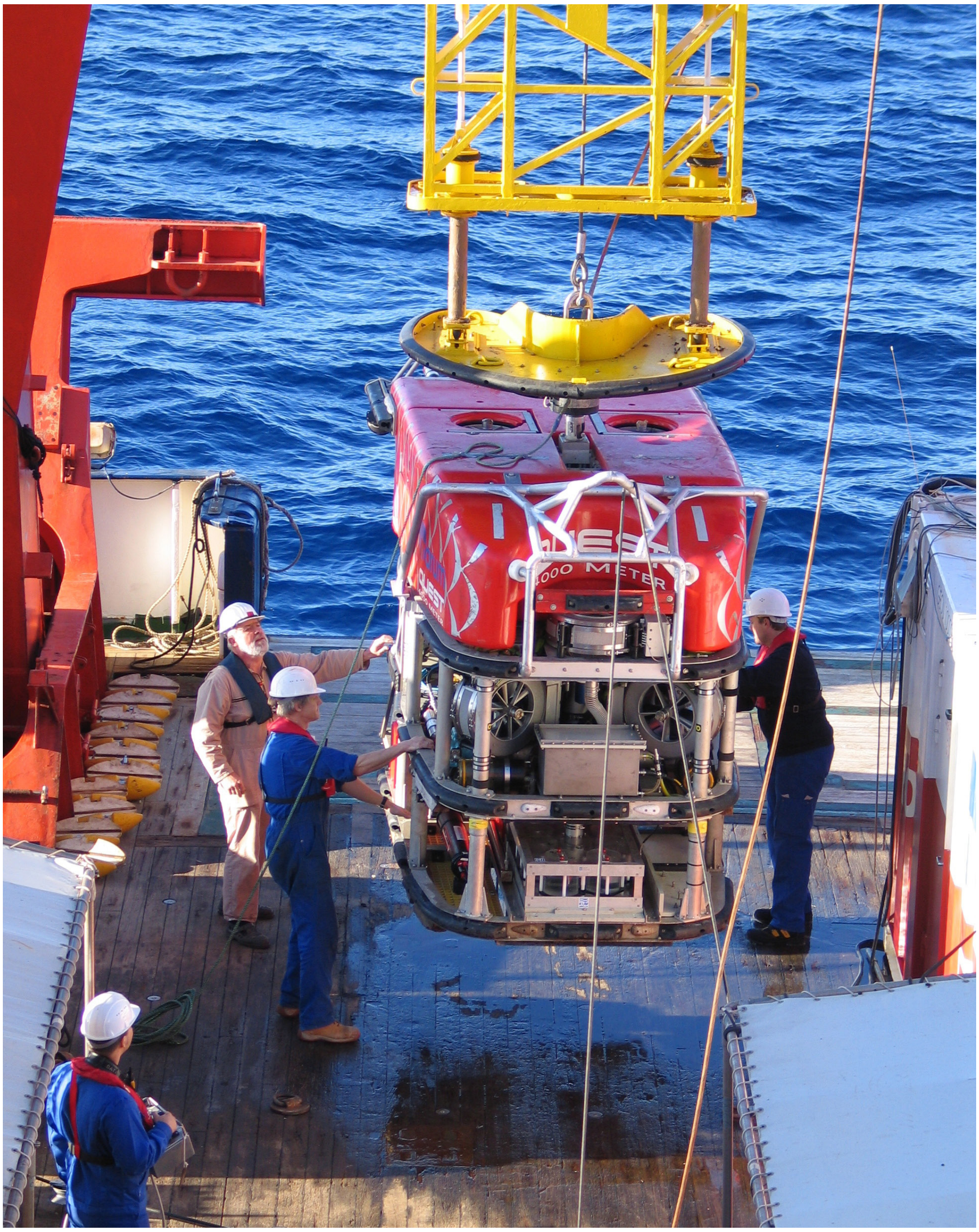
[102] https://www.protectedplanet.net/en/thematic-areas/marine-protected-areas

[103] https://www.cbd.int/aichi-targets/target/11

[104] https://treaties.un.org/doc/Treaties/2023/06/20230620%2004-28%20PM/Ch_XXI_10.pdf

[105] https://www.cbd.int/gbf



Use of the ROV MARUM-QUEST from the research vessel METEOR during an expedition in the eastern Mediterranean

Credit: MARUM – Center for Marine Environmental Sciences, University of Bremen; T. Klein, CC-BY 4.0

or mitigating environmental stressors (Duarte *et al.,* 2020). Conversely, rehabilitation is an action to repair, enhance and/or replace ecosystem processes or components and to improve ecosystem services, although not necessarily to pre-existing conditions (Abelson *et al.,* 2020). Restoration is an attempt to return the ecosystem to a former healthy status, while reduction of impacts and rehabilitation support ecological restoration.

Due to the complexity of ecosystems, restoration is not always successful. Nevertheless, the biological feasibility has been demonstrated for several species: seagrass has been actively restored by transplanting shoots/fragments or by relocating plugs or excavated seagrass mats, known as underwater gardening (Gamble *et al.,* 2021). Harvested natural seaweed populations can also be restored through spore seeding or planting fragments (Oyarzo-Miranda *et al.,* 2023). Restoration can also include restocking, which consists of releasing hatchery-raised juvenile fish at a specific site to restore the natural population to the levels it used to be. This can be performed to recover ecosystems (Abelson *et al.,* 2016) or to recover harvesting capacity (Blanco Gonzalez *et al.,* 2008). As reviewed by Swan *et al.* (2016), in the last five decades, around 500 instances of restocking in the marine environment have been documented; 44% involving coastal invertebrates, 30% involving plants and the remaining 23% involving vertebrates, among which fishes were the majority (51%).

Finally, technological improvements (e.g. for transplanting, seeding and upscaling) are needed to move restoration from small-scale, pilot experiments, to cost-effective restocking strategies that are easy to transfer to end-users, scalable in the field and socio-ecologically sustainable (Abelson *et al.,* 2020). Promoting multidisciplinary actions, co-designed with stakeholders and natural and social scientists, and adaptive management strategies are crucial for restoration to improve social-ecological resilience (Gann *et al.,* 2019). For more on this, see EMB Position Paper N°. 27 on Coastal Resilience (Villasante *et al.,* 2023). The scaling-up of marine restoration activities is necessary to meet the requirements of the EU Nature Restoration Law. More accurate and extensive marine habitat maps that include information on biodiversity structure and function will aid in determining areas suitable for restoration measures and in monitoring the success of restoration projects (Fraschetti *et al.,* 2024). We should also research the future cost of losing resources due to overexploitation and compare this with the present cost of recovering them through greater resource control via restoration activities, to help justify these investments.

5.7 Tools to fill knowledge gaps

As previously highlighted, with over 90% of marine biodiversity remaining undescribed (Mora *et al.,* 2011), there is a real need to fill this gap and further improve our understanding of the role of all marine species in terms of ecosystem functioning and species interactions. Measuring marine biodiversity requires both structured sampling and identification of species and populations. Traditional sampling methods (e.g. quadrat sampling, transect lines, using a net) are suitable for studying coastal populations of seagrass, small animals, fish and shellfish, and birds, but not larger or smaller species. Some ecosystems are not very accessible due to their size or depth, and the mobility of their inhabitants. Thus, technologies such as drones, GPS trackers, environmental DNA[106] (eDNA), Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), active or passive acoustic sensor arrays, remote sensing and image identification are needed. However, sampling the deep Ocean at the appropriate frequency to estimate biodiversity still mostly requires long research cruises to distant places on expensive research vessels. For more information, see EMB Future Science Brief N°. 3 on Biological Ocean Observations (Benedetti-Cecchi *et al.,* 2018), and EMB Position Paper N°. 25 on Research Vessels (Nieuwejaar *et al.,* 2019).

5.7.1 Traditional and new tools for biodiversity monitoring

Taxonomy was the foundation of marine ecology, evolution, and conservation. Since the 18th century, the study of marine biodiversity has been achieved through traditional taxonomy, which has helped to describe thousands of marine species and to make our Ocean and seas less mysterious. However, it is time-consuming, typically with a significant interval (even years) between a species' discovery and its description, causing a backlog of species descriptions. This is most likely due to a lack of available expertise; currently there are very few taxonomy departments or even taxonomy positions available.

Over the last three decades, traditional taxonomy has been enhanced by the emergence of new molecular techniques (e.g. Polymerase Chain Reaction[107] (PCR), DNA/RNA sequencing) followed later by the *-omics* revolution (genomics[108], transcriptomics[109], metabolomics[110] and proteomics[111]). Newer approaches can detect the presence of species and monitor biodiversity faster and in a more cost-effective manner (requiring fewer human resources) than traditional taxonomic approaches, yet they are not meant as a replacement. Rather, traditional and newer approaches need to be integrated and complementary to each other to improve scientific knowledge on biodiversity. Newer techniques have helped to carry out comprehensive surveys and identify rare and cryptic[112] species, and to reveal the biodiversity of the microscopic world. Metagenomics has been applied at most taxonomic levels, from the microbiome of the digestive system of certain species (Tovar-Ramírez *et al.,* 2022) to the detection of elusive organisms not observed during traditional sampling surveys and has revealed our great lack of knowledge about the enormous microbial diversity that exists in the marine environment (Sazhin *et al.,* 2019). Massive sequencing strategies will also help to understand the relationships and functional interactions between the different species in an ecosystem, as well as to determine the presence of unknown pathological agents (i.e. risky viruses and bacteria).

These types of studies need to cover all marine environments, and to be repeated over time, to determine population variations and their association with changing climatic conditions. For instance, fisheries management could benefit from using genetic information to predict a stock's potential to adapt to future climate conditions under various levels of fishing pressures (Andersson *et al.,* 2023).

Monitoring of genetic biodiversity needs efficient tools and indices to help set targets for conservation. Projects that have freely downloadable data (e.g. the Darwin Tree of Life[113] covering species in Britain and Ireland, and ATLASea[114] in France) will establish reference genomes for a wide range of species. However, the variation within species, as well as among and within populations, needs to be mapped to provide a baseline for continuous monitoring that can flag biodiversity loss trends.

These newer approaches for studying biodiversity generate large amounts of data, which require better computational solutions for data storage and for the downstream bioinformatic analyses[115]. Hence, collaboration is needed among scientists to promote knowledge exchange. There is also a need to develop user-friendly and accessible resources that can translate complex genomic data into simplified accessible information that can be communicated to policymakers and society. Thus, an efficient pipeline for DNA sequencing, bioinformatics and taxonomic interpretation of data needs to be developed into a user-friendly platform that can be used by scientific and non-expert users.

5.7.2 Towards integrative taxonomy

Species is the reference unit in life sciences. Yet delimiting

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[106] Environmental DNA is genetic material obtained from environmental samples such as soil, sediment and water, without any obvious signs of biological source material, and used as a proxy for the presence of species.

[107] Polymerase chain reaction is a technique for quickly making large numbers of copies of a specific DNA segment

[108] The study of all of the genes within a cell, tissue organism or ecosystem (i.e. its genome), and their interaction with each other and environmental factors

[109] The study of all the RNA transcripts of a cell, tissue, or organism, across a variety of different biological conditions. This gives an overview of gene expression

[110] The study of all the metabolites present within a cell, tissue or organism. Metabolites are intermediate or final products of metabolic pathways

[111] The study of all the proteins produced by a single cell, tissue or organism

[112] From a taxonomic perspective, cryptic species are groups of organisms that are impossible to differentiate just by looking at them and for which you need molecular markers for identification

[113] https://www.darwintreeoflife.org/

[114] https://www.cnrs.fr/en/pepr/pepr-exploratoire-atlasea-genetique

[115] Bioinformatics is a field of science where computational and statistical methods, and software tools are developed to help understand typically large and complex biological data sets

species remains a challenge for marine biologists and ecologists, with consequences for the conservation and management of biodiversity and ecosystem services e.g. drug discovery in related species, management of fish stock units, food fraud and the illegal trafficking of species. Taxonomy requires context and expertise, including comparisons to previously documented species for which genomes have yet to be obtained. While the advent of genomic approaches can be invaluable for identifying new species, understanding the ecological role of the species in the ecosystem requires formal descriptions of their names, anatomy, biology and provenance. In this context, integrative taxonomy delimits species, combining information from multiple biological perspectives, such as biogeography, comparative morphology, DNA sequences and ecology (Dayrat, 2005).

Under the context of global change, where species are disappearing faster than can be described by any taxonomic method, traditional or molecular, we need precise ecological monitoring and studies of the Ocean and seas, which cannot be achieved without accurate species delineation. It is fundamental to urgently train a new generation of marine taxonomists and systematicians[116] in Europe and globally. This will be imperative for the work that will need to be carried out for the Nature Restoration Law in Europe and the BBNJ agreement globally.

5.7.3 Databases and artificial intelligence

There has been a large increase in the amount of biodiversity information available in different databases. Innovations in the methods used to document biodiversity, for instance by generating biodiversity data through partially or fully automated imaging systems such as within marine observatories, ROVs or AUVs (Durden *et al.,* 2016) are further driving this increase. The value of these approaches could be further enhanced by artificial intelligence, facilitating the handling and processing of large amounts of data (Heberling *et al.,* 2021). This wealth of information could enable unprecedented global biodiversity assessments.

However, coordinating and consolidating data-gathering and analysis initiatives remains a major challenge and requires cross-sector approaches that rely on data generated in multiple contexts e.g. fisheries management, ecosystem modelling, biological observations, etc. Existing bottom-up efforts to archive and digitise biodiversity data in more reproducible and standardised formats, with stricter adhesion to the FAIR principles are to be commended. However, more needs to be done to coordinate these initiatives, so that they result in databases which interface with each other, where knowledge is not lost. There needs to be better integration of the data generated by scientists (either at sea or in labs), other stakeholders e.g. environmental managers and fishers, and the public e.g. via citizen science. Better use of all the available biodiversity data would facilitate future research and management in a realistic timeframe (Guidi *et al.,* 2020). To support this, biodiversity datasets should be integrated into the European Digital Twin of the Ocean. Adherence to Open Science strategies will help to make this data available and enable the inclusion of data that are not currently part of these databases due to lack of time by scientists for their analysis or integration, lack of technology, or lack of interest to share data. As a good example, the EU DTO-BioFlow Project[117] is specifically aiming to identify existing but missing biological data, and support and incentivise its flow into DTO data repositories.

5.7.4 Ecosystem modelling

Marine ecosystem modelling approaches integrate a wide array of data streams, producing results to fill knowledge gaps, improve our understanding of the functionality of an ecosystem and examine the implications of future stressors on these ecosystems based on existing knowledge. Ecosystem modelling is a mature yet rapidly evolving field which can inform marine conservation and management efforts. Single-species models have evolved into more complex coupled models able to integrate physical and biological processes, and deal with numerous ecological processes including interactions across food webs (Heymans *et al.,* 2018). Full ecosystem models now also exist for most regions of the world, allowing us to track the flow of energy through an entire ecosystem (Howell *et al.,* 2021). These models are increasingly being used to estimate changes in marine biodiversity (Coll *et al.,* 2016) and will be crucial for the success of the European Digital Twin of the Ocean. Various EU projects are currently working on this including EcoScope[118], ClimeFish[119] and MarinePlan[120]. Such tools can be especially important to simulate outputs of different management scenarios, enabling policymakers to understand the costs and benefits of different approaches e.g. Hansen *et al.* (2019). As such, they are important tools to inform ecosystem-based management and select appropriate management approaches, taking an ecosystem overview rather than focusing on single targeted species. Uncertainty, however, remains a concern and the need for reducing sources of uncertainty is still a major priority for future research. For more information on marine ecosystem modelling, see EMB Future Science Brief N°. 4 (Heymans *et al.,* 2018).

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[116] Systematics is the part of biology that deals with the system of classification of living organisms and studying their relationships to each other

[117] https://dto-bioflow.eu/

[118] https://ecoscopium.eu/

[119] https://climefish.eu/

[120] https://www.marineplan.eu/

5.8 Recommendations

5.8.1 Recommendations for policy and management

- Assess and compare the future cost of losing resources due to overexploitation and other human activities with the present cost of recovering them through greater resource control, as restoring ecosystem functions is costly. This will require national policies and legal measures coupled with the appropriate incentives to ensure that restoration, management and rehabilitation is sustainable and locally appropriate. It also requires a shift from single-species perspectives towards managing marine ecosystems holistically, benefitting all species, habitats and ecosystem functions;

- Support the restoration and management of degraded marine ecosystems, and ensure that such activities involve local actors and that local communities also gain the benefits;

- Develop innovative area-based management approaches, including MSP, to balance the needs of potential users and sustainability of marine ecosystems;

- Include the risk of invasive species through ‘Ocean sprawl’ in impact assessments through independent environmental monitoring studies when authorising coastal urbanisation activities and offshore installations;

- Promote Open Science initiatives to connect biodiversity databases to the European Digital Twin of the Ocean and develop applications to sort information to make it easily accessible for end-users. The information should be regularly updated, available in several languages and contain information about all types of organisms, from viruses and bacteria to larger invertebrates, fishes and mammals; and

- Promote citizen science to improve our knowledge of invasive species.

5.8.2 Recommendations for research and monitoring

- Research the spatial-temporal distribution of marine organisms and the effects of environmental stressors on marine biodiversity, to provide insight into the adaptive potential of marine organisms under current and future climate scenarios. This should cover all marine environments and should be repeated over time;

- Study the impacts of emerging and expanding human activities on marine biodiversity to ensure we have the knowledge to effectively manage such activities in the future;

- Develop more knowledge on how existing and new coastal and offshore infrastructure affect biodiversity, and how this should be monitored;

- Characterise and monitor marine biodiversity in a holistic manner at all taxonomic levels, habitat types and ecosystems by using a variety of methods, including traditional and integrative taxonomy and new genomic methods;

- Conduct multidisciplinary research combining new genomic tools with spatially and temporally resolved models into an ecological framework that includes biophysical modelling of dispersal and connectivity to predict survival and migration patterns of key marine species;

- Develop efficient monitoring tools to measure the genetic variation of important species, including new applications such as real-time DNA sequencing of fish stocks, to be available onboard fishing and research vessels;

- Study and monitor the spatio-temporal microbial distribution in marine ecosystems, and predict future epidemic risks from spread of microbes introduced by invasive species, or from increased resistance to antibiotics used in fish farms;

- Evaluate the epidemiological, genetic, and ecological consequences of invasive species, including assessing the risks to the native ecosystems, and studying the responses of invasive species to the present and future environmental conditions and drivers of change (e.g. climate and increasing human activities);

- Study the current risk factors for ecosystems and humans present in degraded marine environments and how to restore them, identifying what can be restored, what should be prioritised for restoration, and the costs associated with these efforts. The potential benefits of integrating active and passive restoration, co-designed with local stakeholders should also be further investigated;

- Develop initiatives to promote the recovery of knowledge that is being lost and to digitise what is already known; and

- Train a new generation of marine taxonomists and systematicians in Europe through the reinforcement of dynamic collaborative networks, the mainstreaming of taxonomy training schools, and reintegration of this fundamental knowledge into university curricula to ensure this expertise is not lost.

6

Directing our next steps

Credit: Philipp Deus, Pexels

Since the first iteration of Navigating the Future in 2001 (NFI), we have called on the European community to work together to ensure that marine research is coordinated at a European level, and that Europe ensures that the governance of its marine waters is undertaken in a responsible way (NFII). We have also highlighted the importance of climate change, issues surrounding biodiversity and the importance of ecosystem-based management (NFIII), the importance of societal challenges such as resource extraction (NFIV), and of working towards sustainability science (NFV), all of which link to the chapters within this document. In this iteration of Navigating the Future, we specifically highlight the importance that the Ocean will have to play in solving the crises we have created.

Important work has been conducted since the publication of NFI 23 years ago, including the collaborations that are now taking place within sea basins, and across and beyond scientific disciplines. We have also enhanced the way we conduct science through research enablers such as Ocean observing, modelling, capacity development, citizen engagement and the virtual Ocean called for in NFV. The marine research community has evolved and is now generating innovative solutions to societal challenges. However, more can be done to conduct research to develop our understanding of the links between the Ocean and the wider Earth system, i.e. people, climate, fresh water and biodiversity, without doing further harm. It is now time for the community to consider its own role. We need to lead by example and ensure that our research and collaborations are conducted in an ethical, sustainable and environmentally sensitive manner.

A greener, more ethical way of doing science includes using reusable sensors and instruments so that we do not throw instruments overboard with no plans to retrieve them. Greening research vessels, as proposed by the European Commission's 'Fit for 55' initiative[121], and further coordination of research cruises to be complimentary, will help to reduce the carbon footprint of marine research. The EuroFleets projects[122] have coordinated this to some extent, but more should be done to ensure that these cruises are optimised at a European level. We also need to consider the carbon footprint of the travel involved in each research project, and conduct an ethical cost-benefit analysis of doing harm versus gaining knowledge to answer the question of how much harm can an ethical research project bear?

We need to create an inclusive culture in research, constantly questioning the traditional way of working to ensure equal and equitable opportunities without gender and diversity discrimination and ensure that European research projects do not enable 'helicopter' or 'colonial' science[123]. European science has long relied on the exploitation of (former) colonies and their peoples. Decolonising science means addressing perceptions of cultural superiority, reflecting on how European empires affected the development of science, thinking about the political contexts within which we have done our science and encouraging actions to dispel modern prejudices based on concepts of race, gender, class and nationality. Decolonisation will make science more appealing by integrating its findings with questions of justice, ethics and democracy.

In addition, European science has fallen behind in the inclusion of local and traditional knowledge in the scientific endeavour. European marine (natural) science does not include these knowledge systems at present. We need to learn from other scientific fields and other regions of the world to ensure that we use all available knowledge systems to minimise our impact on the Ocean.

The marine research community should also play a role in ensuring that interactions outside their own communities are as effective as possible. Engaging in science communication and outreach with other stakeholder groups will help increase science literacy and awareness of the topics raised within this document, and hence increase the potential for these interactions to result in action.

Through dedicated research over the past 20 years, we have realised how important the Ocean is for mitigating and adapting to climate change, and for mitigating the global biodiversity crisis. However, as highlighted in this document, it is only now becoming clear how important the Ocean is in ensuring abundant and safe fresh water and a habitable planet for humanity.

The critical research underpinning this understanding is at present largely funded via a series of often disconnected, short-term projects, which provide critical observations and knowledge to elucidate this problem. However, this short-term funding is at odds with the interconnected, large-scale, and long-term nature of the issues being addressed. Therefore, long-term (decadal) and sustained research funding is needed to ensure ongoing support to this vital research.

Our critical Ocean and freshwater systems are being impacted by a wide range of different stressors. To monitor, assess and address the adverse cumulative impacts of multiple, co-occurring anthropogenic stressors, we require coordinated environmental legislation, and harmonised and integrated monitoring and assessment systems. Currently, fresh water, climate, biodiversity, human health and wellbeing, and the Ocean are managed by different authorities, who may focus on different issues and respond to different legislation. This often leads to a fragmentation of observation and monitoring efforts, with different bodies using different procedures, calendars, and assessment and evaluation methods. This in turn creates inefficiency, duplication of efforts, data and information gaps, the risk of delivering incoherent conclusions, and difficulties in

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[121] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal/fit-55-delivering-proposals_en

[122] https://www.eurofleets.eu/

[123] https://theconversation.com/decolonise-science-time-to-end-another-imperial-era-89189?xid=PS_smithsonian

synthesising and interpreting the information gathered into coherent and comprehensive assessments. What is required is a multi-level, multi-purpose agenda and framework, capable of acknowledging, accommodating, and integrating the different priorities and objectives of different authorities into a larger and comprehensive system, that is co-owned and jointly managed (Solidoro, 2021). Aspects of this are being addressed within the scope of the European Ocean Observing System[124] (EOOS), which has been championed by the European marine science community for the past 20 years but needs institutional support both from the EC and Member States. Without this support, it will be difficult for Europe to manage the large-scale impacts that will befall its people through the triple threat of climate change, pollution and biodiversity loss.

The Ocean will not be able to provide the services that society needs without effective governance. Strong, adaptive and inclusive Ocean governance is required for the marine research community to be able to provide the Ocean observations, modelling and forecasting needed to understand the impact of the climate change, pollution and biodiversity crises. One new instrument that is currently being driven by the EU and the Government of France is a possible International Panel for Ocean Sustainability (IPOS) (Gaill *et al.*, 2022), which might be a useful instrument to help Nations with their sustainability questions. However, this possible IPOS must build on the work done by IPCC, IPBES, the World Ocean Assessment and other global assessments, to give concrete solutions to the issues Nations have in the Ocean space. The vision for this platform will be unveiled at the UN Ocean Conference in Nice in 2025, but it will be up to the UN to legitimise the work of the 'Towards IPOS' team[125].

Solving the Ocean's problems will require concerted effort from policymakers, politicians, industry, the public and the finance sector. Unlike climate finance, which invests in either climate mitigation or adaptation[126], Ocean finance (Sumaila *et al.*, 2021) invests in sustainable Ocean management and conservation, including to establish and manage MPAs, sustainable fisheries, Blue Carbon initiatives and the development of offshore renewable energy installations. The marine science community should work with the global financial sector and policymakers to highlight the most important places where sustainable and equitable Ocean finance is needed. Currently, financial involvement in this area is diverse and uneven, ranging from small, local projects with environmental awareness, such as community-based coastal clean-up initiatives, to more substantial funding from transnational corporations in significant sectors such as mineral extraction, energy and fishing, which might not necessarily be sustainable.

Credit: Nico Marin / Ocean Image Bank

Plastic pollution on a beach

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[124] https://www.eoos-ocean.eu/

[125] https://ipos.earth/

[126] https://www.lse.ac.uk/granthaminstitute/explainers/what-is-climate-finance-and-where-will-it-come-from/


Credit: EMB

Managing the land-Ocean interface is critical for a healthy Ocean

To ensure that our interactions with the Ocean are sustainable, we will need to adopt new financing methods that complement or replace existing investment or financial products (e.g. debt for nature swaps[127]). These instruments should mobilise private sector investments in climate and Ocean finance, such as green bonds or Blue Carbon credits. These investments could also hold 'blue labels' to indicate the expected biodiversity, conservation and societal benefits. It is necessary that the scale of capital activated meets the scale of the challenges we face. This will require sustained political commitment, as well as effective governance and regulation to ensure transparency, accountability and alignment with the goals of Ocean conservation and sustainable use. An example is the commitments that underpinned the 'Loss and Damage'[128] fund for vulnerable countries experiencing the worst effects of climate change, such as rising sea-levels, storm inundation, crop damage and fires[129] which was adopted at COP27[130] and became operational at COP28[131]. Significantly more effort is needed in terms of diversifying donor pledges and identifying novel funding instruments that are adapted to those whose lives and livelihoods are most affected. Target 19 of the Kunming-Montreal Global Biodiversity Framework which asks to *"Mobilise US $ 200 billion per year for biodiversity from all sources, including US $ 30 billion through international finance"* is an example of the innovative funding reallocation schemes that will be needed to enable the necessary infrastructure for future Ocean research, conservation and sustainable development.

The existing Ocean regulatory regime is underpinned by UNCLOS, and while ground-breaking at the time negotiations concluded in the early 1980s, it leaves many issues unaddressed. Most of the Ocean is still defined as 'international waters', requiring the cooperation of many countries to manage it properly. There is also a pressing requirement to integrate Ocean needs into an emerging framework of government-agreed environmental targets that cut across multiple areas and include biodiversity and climate change mitigation, adaptation and resilience. The UN Biodiversity Beyond National Jurisdiction Treaty will improve standards and introduce more consistency into the environmental impact assessments of human activities on the high seas, but this needs to be integrated with national standards to ensure consistency across the global Ocean. Although the new BBNJ agreement goes some way towards addressing the use of these Areas Beyond National Jurisdiction, its ratification and implementation is dependent on sound science in these areas where nobody has jurisdiction. This implies that science and observations should cross these boundaries to be conducted with a global approach within and outside national waters, and national science agendas should be expanded to include the importance of the Ocean outside national waters. GOOS and the new IOC Working Group on Ocean Observations in Areas under National Jurisdiction (WG-OONJ) are leading the way in observing these areas with ARGO floats etc., but to really manage these areas properly will require concerted efforts from all nations and many more and different observations. Europe should lead the way in ensuring that we play our part in these areas.

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[127] https://www.undp.org/future-development/signals-spotlight/new-wave-debt-swaps-climate-or-nature

[128] https://unfccc.int/news/cop27-reaches-breakthrough-agreement-on-new-loss-and-damage-fund-for-vulnerable-countries

[129] https://www.unep.org/news-and-stories/story/what-you-need-know-about-cop27-loss-and-damage-fund

[130] https://www.un.org/en/climatechange/cop27

[131] https://www.cop28.com/en/news/2023/11/COP28-Presidency-unites-the-world-on-Loss-and-Damage

Within national territorial waters, MSP can contribute significantly to mitigating climate change by promoting the development of renewable energy (e.g. identifying suitable locations for offshore wind farms and ensuring that they are built in a way that minimises their environmental impact), reducing GHGs from shipping (e.g. identifying areas where speed limits or emission standards could be enforced), and protecting marine ecosystems and their carbon sequestration capacity (e.g. identifying areas that are particularly important for carbon sequestration and regulating human activities in those areas to minimise their impact). MSP can also ensure that we protect enough biodiversity to mitigate the biodiversity crisis and that there is enough natural Ocean space left to reap the benefits to human health that the Ocean can provide. These health benefits are well described in the High-Level Panel for a Sustainable Ocean Economy document on Ocean and Human Health (Fleming *et al.,* 2024), which also highlights the importance of implementation of the BBNJ and other international agreements, the need for the precautionary principle to prevent future harm and achieve sustainability, equity, and inclusion, and ensuring that the best decisions are made for both the Ocean and people.

In Europe, governance is still limited at the land-Ocean interface. The MSP Directive goes a long way towards managing our interactions with the Ocean, but it does not govern what we do on land. Integrated Coastal Zone Management[132] (ICZM), which is prevalent in other parts of the world, is an effective way to govern the intersection of Ocean and land. ICZM should be adopted more widely in Europe to ensure that our activities in the coastal zone do not impact marine ecosystems, nor impact people living in coastal areas. Furthermore, ICZM is critical but not sufficient. If we do not address pollution on land, through e.g. the Nitrates Directive and the WFD, we will not achieve the Ocean we need to help mitigate the climate and biodiversity crises we have created, and we will not ensure clean and safe waters for wildlife and humans alike.

Even if the marine research community, financiers and policymakers achieve all of the recommendations made thus far in Navigating the Future VI, we will still not be able to solve all the known problems the Ocean faces. Without citizen engagement and political will, we will never resolve these problems. Policymakers can only create the needed policies if they get the mandate from their leaders, who are often politicians. Scientists are constantly asked to do more, to communicate more, to make their science more policy-relevant, to train more Ocean professionals, and to pivot to new challenges. However, the main focus of marine science should be to do sound and innovative science. Regardless, because scientists care about the environment and are engaged to ensure a healthy Ocean, they are pressed to undertake evermore tasks, which reduces their time to do good science. The burden of the Ocean's and the planet's health cannot be solely laid at the door of scientists.

As the European marine science community highlighted in the Vigo Declaration[133] *"we stand ready to work together to provide collaborative, science-based policy advice to all levels of governance (from local to international)"*. To achieve climate neutrality, to reduce pollution and to restore nature, we need integrated land-sea policies and management, sustained, and better coordinated Ocean observations and committed citizens that have empathy towards the Ocean. Without the political will, that can only be created by citizens' push for healthy ecosystems, we will not achieve the healthy Ocean and planet we need. Without politicians really engaging in the science-policy interface, scientists will continue to work without making an impact, regardless of the time and energy they put into the process. When politicians engage in science-policy workshops and conferences without listening, they pay lip service to addressing the large-scale policy questions that citizens ask of them. Politicians who engage in these events should therefore give the scientific community the courtesy of taking time to listen to the scientists they address.

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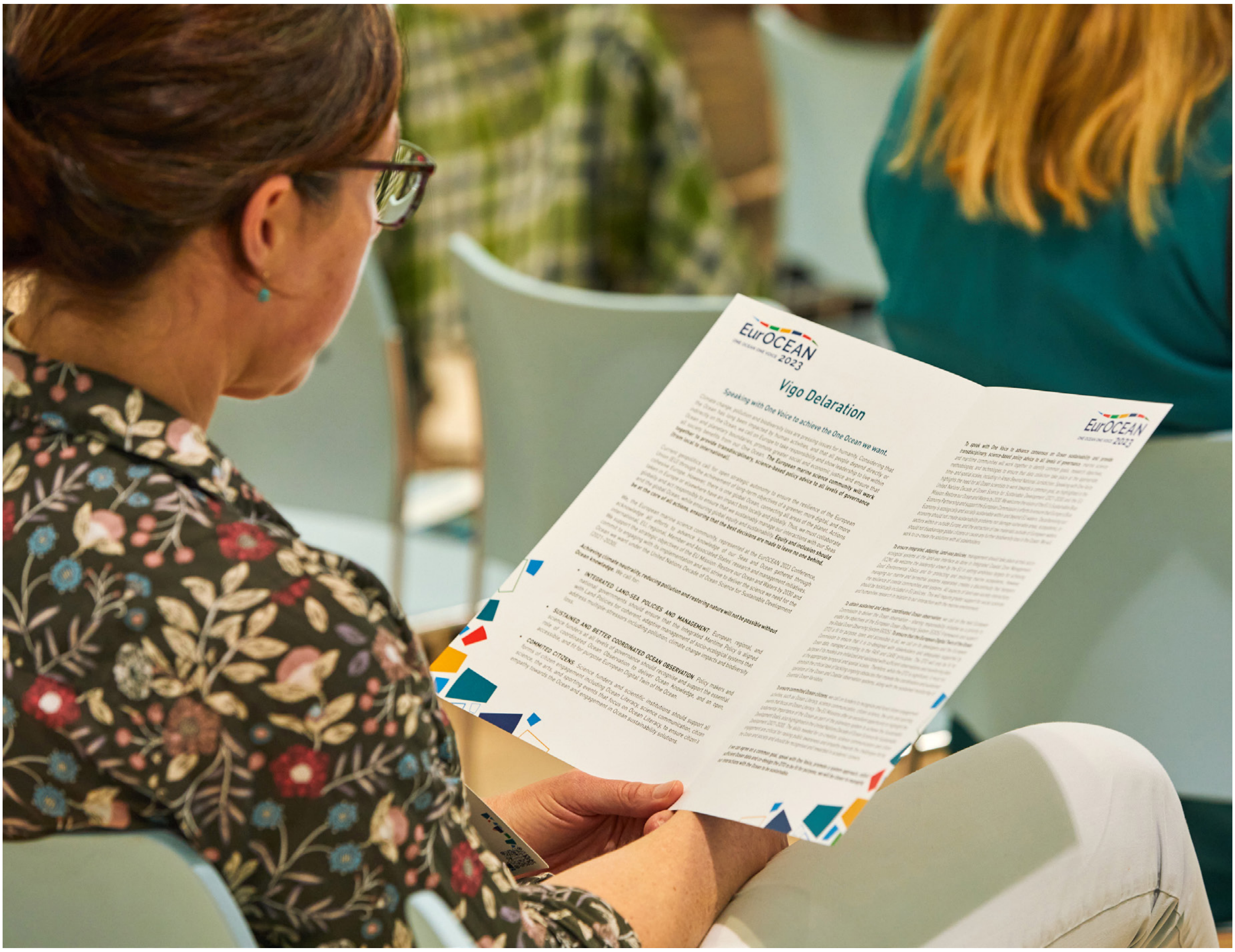
[132] https://www.eea.europa.eu/help/glossary/eea-glossary/integrated-coastal-zone-management

[133] https://www.euroceanconferences.eu/vigo-declaration



The Vigo Declaration published at the EurOCEAN 2023 Conference in Vigo, Spain

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List of abbreviations and acronyms

ABNJ	Areas Beyond National Jurisdiction
AMOC	Atlantic Meridional Overturning Circulation
AORA	Atlantic Ocean Research Alliance
AUV	Autonomous Underwater Vehicle
BBNJ	Biodiversity Beyond National Jurisdiction
CBD	Convention on Biological Diversity
CEC	Contaminants of Emerging Concern
CICES	Common Classification of Ecosystem Services
CO_2	Carbon dioxide
COP	Conference of the Parties
CPU	Central Processing Units
DNA	Deoxyribonucleic acid
EC	European Commission
ECV	Essential Climate Variables
EEA	European Environment Agency
EMBRC	European Marine Biological Resource Centre
EMODnet	European Marine Observation and Data Network
EMSO-ERIC	European Multidisciplinary Seafloor and Water Column Observatory – European Research Infrastructure Consortium
EOOS	European Ocean Observing System
EOV	Essential Ocean Variables
E-PRTR	European Pollutant Release and Transfer Register
ERA	European Research Area
ESF	European Science Foundation
EU	European Union
FAIR	Findable, Accessible, Interoperable and Re-usable
FP	Framework Programme
GBON	Global Basic Observing Network
GCOS	Global Climate Observing System
GHG	Greenhouse gases
GOOS	Global Ocean Observing System

GPS	Global Positioning System
GPU	Graphics Processing Units
HELCOM	Helsinki Commission
ICCI	International Cryosphere Climate Initiative
ICES	International Council for the Exploration of the Sea
ICZM	Integrated Coastal Zone Management
IOC-UNESCO	Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization
IPBES	Intergovernmental Panel on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPOS	International Panel for Ocean Sustainability
IoT	Internet of Things
IUT	Internet of Underwater Things
MPA	Marine Protected Area
MSFD	Marine Strategy Framework Directive
MSP	Marine Spatial Planning
N_2O	Nitrous Oxide
NF	Navigating the Future
NGO	Non-Governmental Organisation
OECD	Organisation for Economic Co-operation and Development
OSPAR	Oslo-Paris Commission
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyls
PCR	Polymerase Chain Reaction
PFAS	Per- and poly-fluoroalkyl substances
PFOS	Perfluoroctanesulfonates
RNA	Ribonucleic acid
ROV	Remotely Operated Vehicle
RSC	Regional Sea Conventions
SDG	Sustainable Development Goals
SEEA	System of Environmental Economic Accounting
SIDS	Small Island Developing States
SROCC	Special Report on the Ocean and Cryosphere in a Changing Climate

UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
UNCLOS	United Nations Convention on the Law of the Sea
UNEP	United Nations Environment Programme
UWWTD	Urban Waste Water Treatment Directive
WFD	Water Framework Directive
WG-OONJ	IOC Working Group on Ocean Observations in Areas under National Jurisdiction
WHO	World Health Organization
WMO	World Meteorological Organization
WORMS	World Register of Marine Species

Glossary

Adsorption - The attraction of molecules onto the surface of a solid

Bayesian inference - A statistical technique where the probabilities of an event occurring are updated when new data are gathered

Bioaccumulation - A process that occurs over time, while biomagnification occurs through the food web

Biochemical markers - Molecules produced during the process of disease that can be tracked

Bioinformatics - A field of science where computational and statistical methods, and software tools are developed to help understand typically large and complex biological data sets

Biomagnification - The cumulative process of storage of chemicals in an organism through the diet

Chitosan - A product which comes from shellfish exoskeletons and is used in the manufacture of medication

Clathrates - Natural gas hydrates; a solid similar to ice but with methane trapped by a cage made of water molecules

Colloid - A mixture in which one substance consisting of microscopically dispersed insoluble particles is suspended within another substance

Cryptic species - Groups of organisms that are impossible to differentiate just by looking at them and for which you need molecular markers for identification

Driver - Any natural or human-induced factor that directly or indirectly causes a change in an ecosystem or social situation

Eco-corona biofilms - A layer of organic substances or biomolecules surrounding micro and nanoplastics

Ecosystem engineer - Species that create, modify and/or maintain a habitat or ecosystem

Environmental DNA - Genetic material obtained from environmental samples such as soil, sediment and water, without any obvious signs of biological source material, and used as a proxy for the presence of species

Foundation species - A species that has a large contribution towards creating a habitat or ecosystem that support other species

Genetic markers - DNA sequences with a known physical location on the chromosome which can then help understand the links between a disease and the gene responsible

Genomics - The study of all the genes within a cell, tissue organism or ecosystem (i.e. its genome), and their interaction with each other and environmental factors

Keystone species - Species which have a larger impact on their environment than would be expected from their biomass, highly influencing the structure of biodiversity and the function of the ecosystem

Medicane - Mediterranean tropical-like cyclones or hurricanes

Meridional overturning circulation - A system of currents that circulates water within the Ocean, bringing warm water north and cold water south

Mesoscale convective system - A complex of thunderstorms that becomes organised on a scale larger than the individual thunderstorms but smaller than mid-latitude cyclones, and normally persists for several hours or more

Metabolomics - The study of all the metabolites present within a cell, tissue or organism. Metabolites are intermediate or final products of metabolic pathways

Meteotsunami - Atmospherically generated shallow-water waves caused by a rapid change in barometric pressure, which displaces water

Microplastic - Generally recognised as plastic items smaller than five millimetres to a minimum limit of one micrometre

Niche - The match of a species to a specific environmental condition

Ocean sprawl - The removal or transformation of marine habitats through the addition of artificial structures

Ocean ventilation - The transfer of heat, salt, oxygen, and carbon from the surface to the deeper parts of the Ocean

Phenology - The study of the timing of recurring biological events (e.g. seasonal migrations or spawning), the causes of their timing in relation to biotic and abiotic forces, and the interrelation among phases of the same or different species

Phenoxy herbicides - A class of acidic herbicides that are difficult to extract from aqueous matrices

Plastisphere - The microbial community attached to plastic that is distinct from its surroundings, forming a new ecosystem

Polycentric Governance - A system of governance which has multiple decision centres

Polymerase chain reaction - A technique for quickly making large numbers of copies of a specific DNA segment so that it can be studied

Prions - Misfolded proteins that can transmit untreatable, infectious, and fatal brain diseases in mammals

Proteomics - The study of all the proteins produced by a single cell, tissue or organism

Sessile - An organism that is immobile and is unable to move from its location

Shifting Baseline Syndrome - A gradual change in the accepted norms for the condition of the natural environment due to a lack of experience, memory and/or knowledge of its past condition

Social-Ecological Systems - A concept for understanding the highly connected interactions between societies and ecosystems

Sorption - A physical and chemical process by which once substance becomes attached to another

Steric change - Change in the volume of seawater due to changes in temperature or salinity, which affect its density

Stratification - Separation of water with different properties (i.e. density, salinity, and temperature) into layers acting as a barrier to mixing

Stressor - Pressures or dynamics that impact ecosystem components or processes caused by human and associated activities, with negative results

Surfactant - Chemical compounds found in cleaning products

Surrogate models - Fast-running approximations of complex time-consuming computer simulations

Systematics -The part of biology that deals with the system of classification of living organisms and studying their relationships to each other

Transcriptomics - The study of all the RNA transcripts of a cell, tissue, or organism, across a variety of different biological conditions. This gives an overview of gene expression

Annex 1

Members of the European Marine Board Working Group on Navigating the Future VI

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