FMRI
FUTURE MARINE RESEARCH INFRASTRUCTURE
HARNESSING CUTTING-EDGE CAPABILITIES

A UK Science Requirements Framework for Future Marine Research Infrastructure

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UKRI
Natural Environment Research Council

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Preamble

The planning for Future Marine Research Infrastructure (FMRI) must be driven by national science requirements that meet the needs of all stakeholders in UK marine science. The Science Requirements Framework (SRF) has been developed by the UK marine science community to specify the knowledge required by society to benefit from the ocean and to ensure the marine environment remains in a healthy state in the future. The science needed to gather this knowledge is specified around five marine science 'Grand Challenges', each focusing on the marine research needs of climate change, marine biodiversity, marine pollution, natural hazards and the blue economy, which outline the steps to enable Marine Science in 2040 and beyond.

'FMRI provides a unique opportunity to take a holistic and forward-looking approach to guiding the UK's future investment in marine research infrastructure to maximise science impact and science value for investment by combining observations and digital tools in new and innovative ways.'

This process is not starting from scratch. It will build on the significant progress made during the Net Zero Oceanographic Capability (NZOC) scoping study (National Oceanography Centre, 2021), particularly Work Package (WP) 1 on Future Science Needs, which includes an in-depth analysis of UK marine science activities.

Within the context of future marine science goals, it is important to articulate science requirements in a way that informs decision making; enabling priorities, interdependencies, synergies, trade-offs and consequences to be considered in context, when recommendations on options for investment in infrastructure are made.

The aim is to have a FMRI SRF available for comment by the UK Marine Science community by Spring 2025, so that options for investment can be considered against that framework.

Contents

PART 1: Strategic Overview and Context

1. Introduction

The ocean is fundamental to planetary habitability and human prosperity. Moreover, the ocean is a critical element within the broader Earth system, the components of which are connected through physical, chemical, biological and geological processes. Interactions and feedback between these components have driven the (co-)evolution of the planetary environment and life and will determine how human activity will continue to influence and be influenced by the ocean and wider Earth system. Our ability to observe and use the ocean as an observing platform for other system components (including the atmosphere, cryosphere and lithosphere), is thus vital for investigating how the interconnected Earth system works over multiple timescales. The understanding and ground truthing provided by such observations are, in turn, essential for predicting and managing how natural and anthropogenic climate change, pollution, natural hazards and resource availability will impact human health and activity, and the health and diversity of the biosphere.

Covering >70% of the surface of the planet, representing >95% of the spatial extent of the biosphere and storing 60 times more carbon dioxide (CO_2) than the atmosphere, the ocean largely influences, responds to and records many Earth system processes and impact multiple areas of human activity. The ocean has absorbed 30% of the excess anthropogenic carbon dioxide (Gruber *et al.*, 2019) and 90% of the excess anthropogenic heat generated over the last century (von Schuckmann, Cheng, *et al.*, 2020). Globally, the blue economy is predicted to increase in value to over US$3 trillion by 2030, with the UK component (£46 billion global value added, 2005-2006) growing quickly (OECD, 2016). The ocean dominates the international transport of goods and information (95% of all UK trade, 95% of UK internet traffic, with trillions of pounds of financial trades through submarine cables). In addition to food trade (50% of UK total), the ocean contributes to food security by providing 15% of animal protein and 6% of total protein consumed globally, with the UK spending £4 billion a year on seafood (approx. 2-4% of the total food expenditure). Increasingly, coastal seas are contributing to UK energy security through the expansion of offshore wind (already 15% of UK electricity generation). Globally, US$5 trillion (UK £17 billion) is spent on coastal and marine tourism, reflecting how the value of the ocean to society extends beyond the economy to human health. Direct and indirect experience of the ocean enhances human wellbeing and provides a sense of wonder at our shared planet. Moreover, 10% of the world population live within a few miles of the coast and are hence exposed to natural hazards such as storm surges, sea level rise and tsunami. In the UK, three million people live in coastal communities, no inhabited location is more than 70 miles from the sea and the ocean strongly influences our island weather and climate.

All of the processes, ecosystem services and hazards outlined above are subject to both natural and anthropogenic change. Climate change, pollution, fishing, resource extraction, transport and infrastructure development all impact the capacity of the ocean to provide value to society and society's capability to act as custodians to sustainably manage the ocean. There is uncertainty on the rate at which the ocean can buffer anthropogenic CO_2 emissions into the future, while multiple ocean processes are also under consideration for active atmospheric carbon dioxide removal (CDR). An estimated 60% of the world's major marine ecosystems have been degraded or are being used unsustainably, contributing to the biodiversity crisis. Without significant change, up to 50% of critical marine habitats could be destroyed by 2100 (Hodapp *et al.*, 2023) – e.g., 35-95% of shallow ocean environments (Lotterhos, Láruson and Jiang, 2021), and up to 90% of coral reefs (Freeman, Kleypas and Miller, 2013). A recent study also estimated up to 90% of the world's marine species will be at high or critical risk of extinction by this time

(Boyce *et al.*, 2022). In addition to ongoing resource extraction activities (e.g., aggregates, fossil fuels), the quest for critical metals to facilitate the energy transition is pushing further into the deep sea, potentially impacting the most isolated ecosystems on Earth. A warmer ocean, and melting ice, are leading to altered weather patterns and increasing the frequency of extreme events and coastal hazards. Sea level rise projections indicate that 800 million people will be at risk from coastal flooding and storm surges by 2050, with the global community facing annual costs of over US$1 trillion to coastal urban areas. Communities in developing countries and Small Island Developing States (SIDS) are the most threatened, with women and girls especially vulnerable (UN Women, 2021).

The cumulative impacts of these changes are difficult to predict, both due to the multiple stressors acting simultaneously and, in many cases, a lack of fundamental understanding to underpin the development of conceptual or numerical predictive models. Moreover, multiple elements of the Earth system are characterised by complex feedbacks, which can generate tipping points, where the system can switch to a new state with rapid, substantial and potentially irreversible consequences (Lenton *et al.*, 2008). The ocean contains multiple tipping elements, such as the Atlantic Meridional Overturning Circulation (AMOC), changes in the El Niño Southern Oscillation and Arctic sea ice loss. Ongoing and future ocean observation capabilities thus need to monitor change and potentially provide early warning of tipping points, alongside better fundamental understanding required to enhance predictability. Additionally, the sediments under the ocean are a crucial archive for understanding past Earth system and climate changes, including unravelling the feedback that drove past change, and determining the thresholds at which the system tipped, both informing our models of future change and improving our ability to test them.

Our knowledge of the ocean and broader interconnected Earth system is currently insufficient to fully understand the extent and implications of the changes we are facing. The role of the ocean in climate change, the extent to which the uptake of heat, carbon and energy impacts upon the ocean itself, how human interaction with the ocean affects biodiversity and the implications for extreme events and natural hazards, and hence people, are poorly understood. In the current era of rapid planetary change, expanding global population, changing resource extraction and new climate mitigation strategies, we are at a unique moment in the global ocean governance and public awareness landscape. The ocean is becoming increasingly visible to policy makers and the public. Ocean and ocean-based observations, and the knowledge and understanding that comes from them, will be critical in providing the evidence for effective decision making, at a time when society is demanding we act more sustainably.

1.1. The Future of UK Marine Science

The UK Science and Technology Framework (Department for Science, Innovation & Technology, 2023) highlights that science and technology will be the major driver of prosperity and national security this century, noting the need to strengthen partnerships between public, the private sector and civil society, nationally and internationally, to realise this this ambition. Marine science is the perfect example, demanding strong collaborations to better observe and understand the ocean as a critical component of the global system – coupling the atmosphere to lithosphere, open ocean to coast, and physics to fish – providing a great laboratory for innovation and technological development.

UK marine science is already highly innovative and dynamic, with strength and depth across a broad spectrum of ocean topics that have strong links into our marine economy, including energy, carbon sequestration and food security, with a combined asset value estimated at £211 billion in 2018 (Office for National Statistics, 2021), or 6.1% of total UK economy output (Stebbings *et al.*, 2020). For example, expertise from the marine science community is needed for exciting new developments in the UK's Blue Economy, with links to national security of energy, of food, and of ecosystem services as a climate regulator.

The UK is an international leader in marine science both in terms of volume and impact. UK marine science contributed 8% of global publications in the field in 2018 (Mitchell, 2020) (only exceeded by the USA and China), with the citation impact of these publications being the highest globally (substantially exceeding both the USA and China and other leading countries in Europe). Similarly, and related, the UK is internationally respected as a major contributor to climate and biodiversity policy (Averchenkova, Fankhauser and Finnegan, 2021), giving it a leading role in science-based decisions about the future of the global ocean, often by playing a lead role in global observation and research programmes. However, to maintain and develop this leading position, alongside the benefits it brings for the UK economy and population, UK marine science now needs strategic investment in infrastructure. Access to physical and digital infrastructure is one of eight strategic priorities in the UK Science and Technology Framework (Department for Science, Innovation & Technology, 2023). The UK Government Chief Scientist's Foresight Future of the Sea Report (UK Government Office for Science, 2018; Figure 1.1) highlighted the importance of the ocean to the UK's economic, environmental and governance interests. To enable a growing blue economy, the importance of investment in infrastructure and skills are recognised as critical enablers.

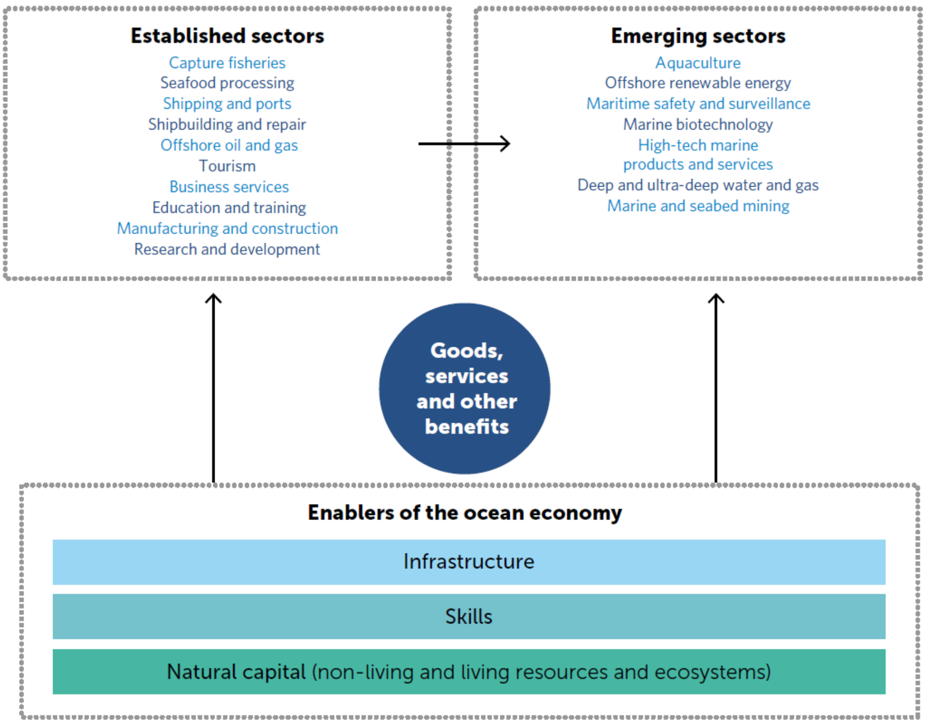

Figure 1.1: The interconnected nature of the blue economy (UK Government Office for Science, 2018).

The FMRI programme provides the impetus and opportunity to bring together a holistic and ambitious vision for UK Marine Science on the timeline of 2040 and beyond. It sits against a backdrop of UK Research and Innovation's (UKRI) infrastructure roadmap (UKRI, 2023b) which identifies potential opportunities to create a step-change in the next generation of infrastructure capability and options for resulting investment and is intended to guide decision-making and identification of priorities to 2030.

UKRI has developed four themes to use as a framework to guide priorities for national research and innovation infrastructure to 2030, encapsulating the processes, activities and needs of world-leading infrastructure in the UK (see Figure 1.2). These themes and framework draw on significant stakeholder consultation, and the drivers and opportunities for the environment sector. The ambitions of each theme can be enabled through actual, digital and distributed laboratories, as well as other infrastructure, capitalising on developing technologies and data availability.

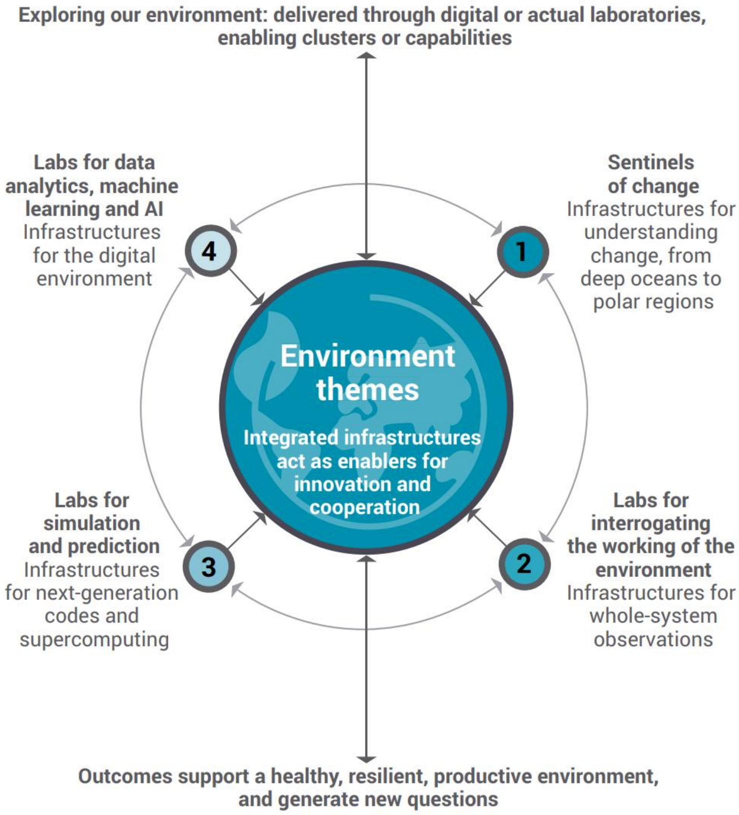

Figure 1.2: Environment sector infrastructure framework (Source: UKRI infrastructure roadmap).

As a guide to informing investment decisions, UKRI's infrastructure roadmap noted the following principles:

a. 'A continued focus on excellence with impact alongside consideration of the strategic drivers, value for money and deliverability of any investments.
b. The appropriate independent advice and input as a vital contribution to decision-making.
c. Decisions to fund new infrastructures taking into account the full lifecycle costs including future operation, staffing, future decommissioning costs, whether there is enough demand, strong governance and incentives to ensure efficient and effective use.
d. Maintaining flexibility to respond to emerging priorities and new financial pressures.

e. Supporting the early-stage scoping and Research and Development (R&D) which may lead to development of new infrastructure capability as part of a developing portfolio.
f. Considering the potential for international collaboration and partnerships.'

Against a background of global change and uncertainty – particularly the Triple Planetary crisis of Climate Change, Pollution and Biodiversity Loss (United Nations Environment Programme, 2024) and greater political and financial uncertainties around the world – the role of understanding the ocean and broader Earth system in charting a resilient and sustainable future for all is ever more present. One of the UN Agenda 2030 Sustainable Development Goals (SDGs; United Nations, 2015) is focused on the ocean (SDG 14: Life below water), however ocean and Earth system science, data and services can be shown to underpin all the SDGs (von Schuckmann, Holland, *et al.*, 2020).

Building on the momentum of the UN Decade of Ocean Science for Sustainable Development, along with technological advances, the next 10 to 20 years present real opportunities to rise to the challenge of advancing our ability to understand and predict the ocean, its role in the Earth system and importance to society in creating a sustainable future.

Other nations are also actively considering how they transition research vessels to green fuels, invest in autonomy and in potentially transformative digital infrastructure. FMRI therefore presents an opportunity to take a holistic and forward-looking approach to making a major positive change to maximise science impact and information value, for investment in maintaining and evolving the UK's marine research infrastructure, while simultaneously taking a global lead in innovation.

The objectives of the FMRI programme are to:

- Establish an environmentally and economically sustainable marine observation and experimentation infrastructure for current and future research.
- Establish a world-leading marine infrastructure portfolio that leads with innovations in measurements, platforms and digital tools to push the frontiers of marine science.
- Pursue an approach that is outward looking, offers global leadership, collaboration opportunities and opens access to under-represented groups.

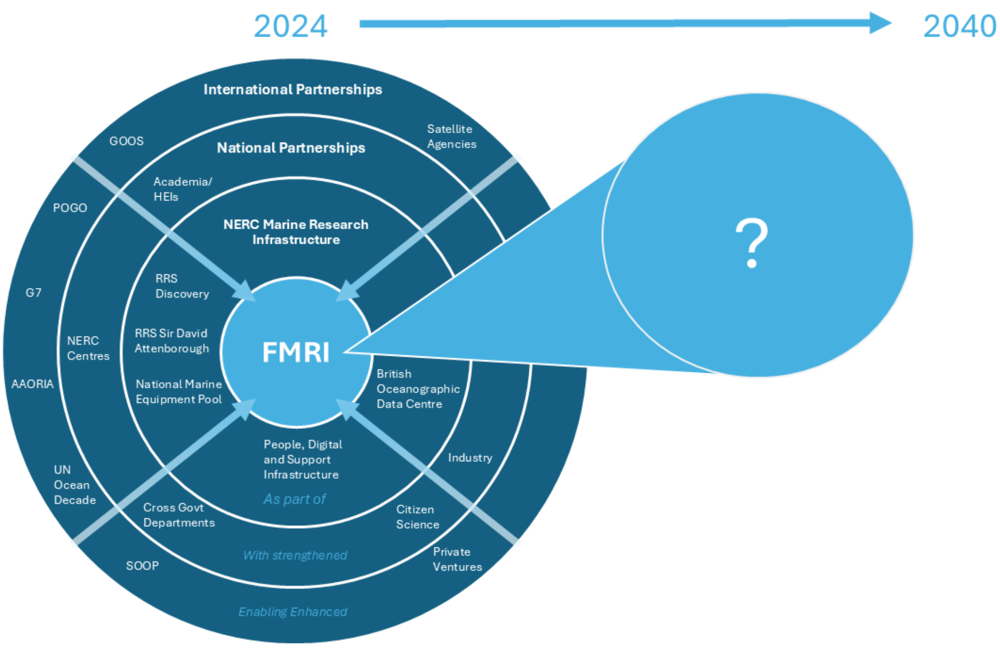

Figure 1.3: FMRI in the context of broader marine research infrastructure.

1.2. NERC Marine Research Infrastructure

The Natural Environment Research Council (NERC) marine infrastructure spans a range of areas (Figure 1.4): two global class research ships operated by the National Oceanography Centre (NOC), a polar class research ship operated by the British Antarctic Survey (BAS), a National Marine Equipment Pool (NMEP) which includes a wide range of specialist sampling and mooring equipment, gliders and autonomous underwater vehicles (AUVs) and the British Oceanographic Data Centre. These capabilities are supported by a wider research environment that includes bases in the UK and Antarctica, research vessels, autonomous platforms and equipment owned and operated by partner UK and international research organisations and Higher Education Institutions (HEIs), and, crucially, the people who operate these facilities and undertake world-leading research. These capabilities play a vital role in enabling NERC/UKRI science both directly in the study of marine systems, and as interacting components of the Earth system. The purpose of FMRI is to invest in this capability, supporting the transition to a modern and sustainable research capability by 2040 that integrates new technologies with proven platforms. This is a time frame that will include the decommissioning of NERC's oldest vessel, the RRS *James Cook*.

Figure 1.4: Non-exhaustive illustration of composition of current UK Marine Research Infrastructure under consideration comprising three global class research vessels, the National Marine Equipment Pool, data management through the British Oceanographic Data Centre (BODC) and associated human capability.

Responding to the UKRI's goal to achieve net zero carbon emissions by 2040 (UKRI, 2023a) and monitoring the planning timelines required to transition our marine research infrastructure, NERC commissioned a scoping study in 2020-2021 on how to build a Net-Zero Oceanographic Capability (NZOC; National Oceanography Centre, 2021). The NZOC report sought to explore how a world-class oceanographic capability could be achieved with a reduced carbon footprint, by presenting a range of options for adopting low or zero carbon technologies. The scoping study comprised work packages focused on both drivers: Future Science Needs, Future Policy and Regulation; and technology enablers: Future Ships, Marine Autonomy, Sensors and Digital Ecosystems. Further discussion of NZOC outcomes, and particularly WP1 on Future Science Needs, can be found throughout this document.

1.3. Working Towards a Vision for Future Marine Research Infrastructure in 2040

To achieve the full FMRI vision and meet the objectives of the programme, it is important to consider new infrastructure within the wider context of NERC's other research infrastructure and the broader landscape (Figure 1.5). While the Marine Science in 2040 document will be used to support a business case for investment in a replacement capability for the RRS *James Cook*, the FMRI programme presents an opportunity to take a forward-looking holistic view of broader future goals in marine science and the use of marine infrastructure in wider observation and understanding of the Earth system. The Science Requirements Framework (SRF) will inform the Business Case to government in the context of the broader capability landscape including components funded separately (e.g. satellite remote sensing, digital infrastructure, capability funded for public good services), strengthened national and international partnerships, and the full vision for marine research infrastructure evolution through 2040 and beyond (proposed future investment tranches). FMRI needs to consider how to maximise data, information, knowledge and understanding values for investment by not just considering investment in technologies, but how we bring these capabilities together so that the whole is greater than the sum of its parts, optimising the combined capability of an integrated system and maximising access to, and utility of data and information. This includes:

- Leveraging a range of vessels, including e.g., research vessels, partnerships with other vessel operators and Ships of Opportunity (SOOP).
- Considering 'autonomy' in its broadest sense, including underway observations, animal tagging, satellite remote sensing, established autonomous sensor networks (e.g. Argo),

ocean gliders, other Autonomous Underwater Vehicles (AUVs) and Uncrewed Surface Vessels (USVs).

- Future digital infrastructure, and people as integrated components of marine research infrastructure.
- National and International Partnerships: strengthening integration with non-NERC infrastructure, at national level, e.g., through the Department for Science, Innovation and Technology (DSIT), including within UKRI, the Met Office, the Department for Environment, Food & Rural Affairs (Defra), the Department for Energy Security and Net Zero (DESNZ) and the Foreign, Commonwealth & Development Office (FCDO), as well as devolved administrations such as Marine Scotland, alongside the infrastructures operated by independent research organisations and HEIs. Also, international partnerships allowing access to infrastructure including bilateral partnerships with key strategic partners, and multilateral collaboration through, e.g., the Global Ocean Observing System (GOOS).

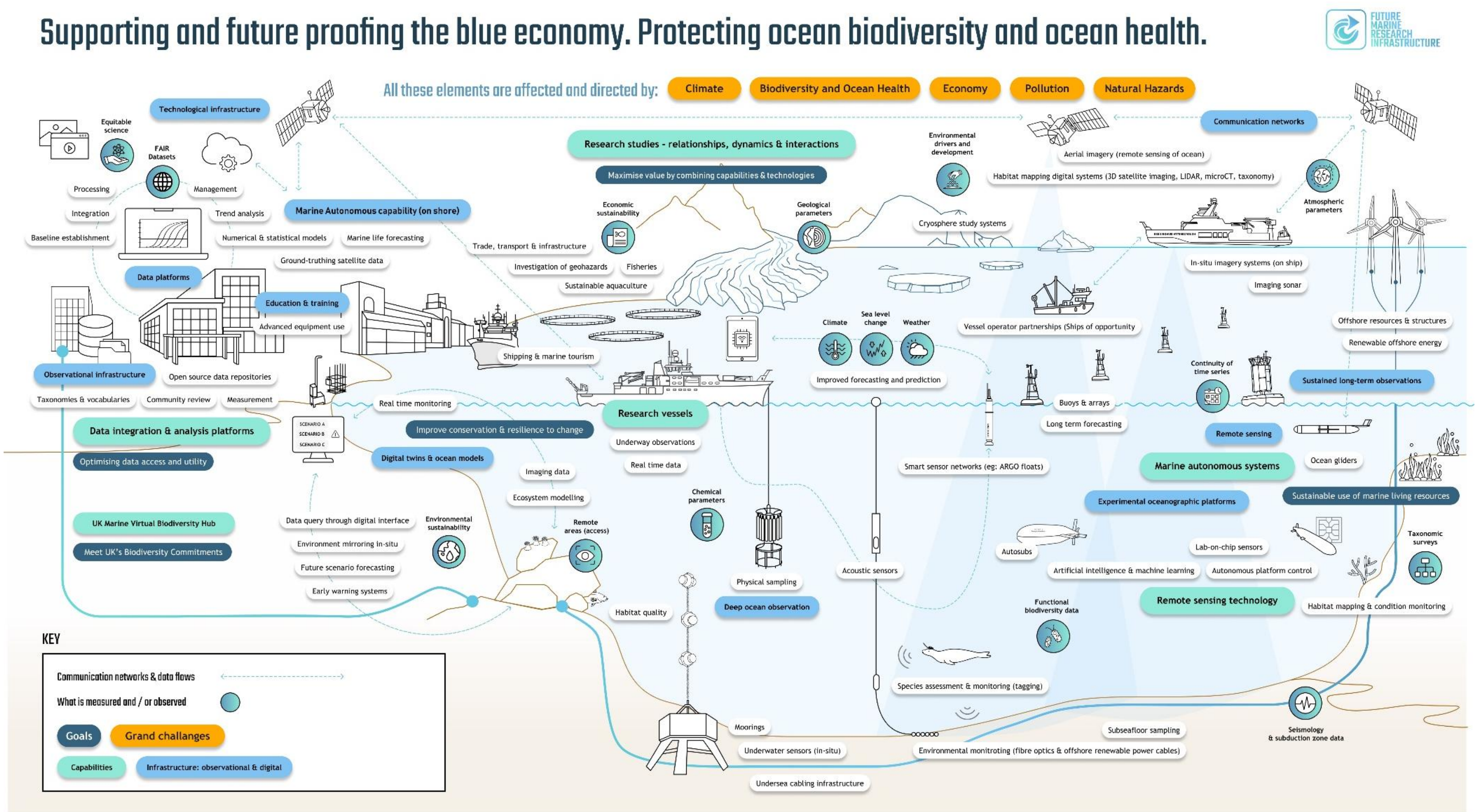

Figure 1.5: UK Future Marine Research Infrastructure in 2040: The vision for a broader integrated capability with partnerships.

2. UK Marine Science in 2024

2.1. Government Science Priorities

The marine economy is set to grow to $3 trillion by 2030 and there is a growing reliance on the marine system for services and resources driven by a growing human population and enabled by new technologies (UK Government Office for Science, 2018). At the same time, the ocean is facing unprecedented challenges arising from direct human impacts and global climate change. These challenges pose risks to marine biodiversity, marine and coastal infrastructure, the marine economy and to human health and wellbeing.

The UK is an island nation, culturally embedded in the ocean, with historically strong maritime industrial, trade and defence interests. For the UK to benefit from increasing opportunities in the marine environment, it must build on its technological and scientific capabilities, which in many cases are world leading, to ensure its place as a leading maritime nation. The UK Government has identified priorities to underpin a consistent strategic approach for the ocean and maritime policies, including for science. In 2009, the UK Government set out five main objectives for the marine environment to achieve the overall vision of *clean, healthy, safe, productive and biologically diverse oceans and seas* (Defra, 2009):

1. Achieving a sustainable marine economy.
2. Ensuring a strong, healthy and just society.
3. Living within environmental limits.
4. Promoting good governance.
5. Using sound science responsibly.

In 2010, the UK Government published the UK Marine Science Strategy for 2010 – 2025 (Defra, 2010). This identified three priority areas and related questions as essential to underpin an ecosystems approach to achieving the strategic vision laid out in 2009:

- Understanding how the marine ecosystem functions:
    - What is the role of biodiversity in maintaining specific ecosystem functions?
    - How long does the seabed take to recover from disturbance such as oil and gas extraction?
    - How do we establish a basis for reliable Good Environmental Status indicators using natural, social and economic sciences?
    - How will increased human activity impact the ecosystems of the deep sea?
- Responding to climate change and its interaction with the marine environment:
    - How will changes to oceanographic conditions as a result of climate change affect marine ecosystems, and how will they impact on society as a whole?
    - How will ocean acidification affect planktonic productivity and other marine organisms?
    - How much will sea level rise around the UK in the next few decades and what will be its effect?
    - What management measures should be adopted to mitigate against and adapt to climate change in the marine environment, including protection of human life?
    - What are the implications of natural variability and how can we distinguish it from anthropogenic causes?
- Sustaining and increasing ecosystem benefits:

- What ecosystem services are provided by the marine environment and how can we influence human behaviour and choices in relation to them?
- What are the comparative environmental effects of newly emerging types of renewable energy, such as wave energy?
- How should the choice be made between marine protected areas (MPAs) and other conservation measures; when MPAs are appropriate, how large they should be and where should they be located to protect biodiversity and enhance surrounding fisheries?
- How do we assess cumulative effects of multiple human activities and the effects on the ecosystem, and how can this translate into taking management action?
- With what precision can we predict the ecological impact of different policy options and the ecological effects of management action?

Whilst a new Marine Science Strategy is yet to be developed, the Foresight Future of the Ocean report (2018) provided recommendations for marine science, including:

- Improving understanding of the ocean through systematic, globally coordinated and sustained global ocean observations and seabed mapping.
- Improved modelling of sea level rise and coastal flooding.
- Technologies to enable modern communication at sea and improve data transfer and battery power.
- Improved understanding of interactions between different stressors, e.g. ocean warming and ocean acidification, and their cumulative impact on the marine environment.
- Identification of 'tipping points' at which marine ecosystems will be unable to recover from projected damage.
- Valuation of marine ecosystems and assets.
- A minimum understanding of the environmental impacts of emerging sectors, to facilitate adequate regulation.

The Foresight Future of the Ocean report also identified key areas requiring science input including addressing threats to biodiversity, reducing plastic pollution and ensuring that the UK Overseas Territories are resilient to the risks posed by climate change. Many of these priority areas map directly to the objectives of the UK Marine Science Strategy. Key to achieving these priorities is the need for interdisciplinary science, international collaboration and enabling the use of big data to drive innovation and modelling of the marine environment.

The Foresight Future of the Ocean report stated that opportunities for UK science and industry primarily related to understanding global-scale change, variability and impacts, identifying new marine resources and the implications of their exploitation, improving predictive capability for hazards and disasters, and developing transformational new technologies to facilitate new activity at sea. This emphasises that the government's objective of a sustainable future marine economy, a healthy ocean and a healthy, just and resilient society requires a knowledge-based relationship with the marine system.

The footprint of UK Overseas Territories and interests has ensured the UK has global interests in marine science. This has been formalised through the Overseas Territories Biodiversity Strategy (updated 2014) which has the objective to 'enable the UK and Overseas Territory Governments to meet their international obligations for the conservation and sustainable use of biodiversity in the Overseas Territories'. There are 14 overseas territories spanning tropical to polar environments that host more than 32,000 species, of which ~1,500 are endemic, although the estimated number of species exceeds 100,000 (Churchyard *et al.*, 2016). The Strategic Priorities of the Overseas Territories Biodiversity Strategy include:

- Obtaining data on the location and status of biodiversity interests and the human activities affecting biodiversity to inform the preparation of policies and management plans (including baseline survey and subsequent monitoring).
- Preventing the establishment of invasive alien species and eradicating or controlling species that have already become established.
- Developing cross-sectoral approaches to climate change adaptation that are consistent with the principles of sustainable development.
- Developing tools to value ecosystem services to inform sustainable development policies and practices.
- Developing ecosystem-based initiatives for the conservation and sustainable use of the marine environment.

The UK has supported its 14 overseas territories through financial support for a range of activities such as eradication of invasive species, valuation of ecosystem services to inform sustainable development, collation of data and development of spatial mapping and planning tools, development of sustainable fisheries, as well as participation in regional fisheries management organisations (RFMOs) and conservation actions and programmes through the Darwin, Darwin Plus, and Blue Belt programmes and the Conflict, Stability and Security Fund. It also provides technical expertise and scientific support from UK Government Agencies and scientific institutions.

2.2. The International Dimension

The UK's interests are directly affected by the economy, environment and security of the marine system globally. It therefore has a direct interest in the stable and effective governance of the marine environment and interacting components of the Earth system. The UK maintains a proactive role in international ocean affairs, shaping new international treaties such as the recent Biodiversity Beyond National Jurisdiction (BBNJ) Agreement, as well as implementing nationally, and helping other countries to implement existing treaties and their requirements, such as the UN Convention on the Law of the Sea (UNCLOS) and the Convention on Biological Diversity (CBD). Table 2.1 outlines 23 International Agreements and Conventions relevant to the marine system to which the UK is a signatory, along with the requirements of each for environmental management and protection and international cooperation (Rogers *et al.*, 2023). All of these requirements need input from science in terms of monitoring of the marine environment and biodiversity, the analyses of data on marine species, the environment and human activities for sustainable exploitation or protection of biodiversity, modelling for prediction, marine technology development, as well as direct international collaboration in marine science and capacity building. The UK also hosts the International Maritime Organisation (IMO), the UN Implementing Agency for regulation of shipping, maritime safety and marine pollution. Many of these conventions/agreements have science and technical committees (e.g. the Subsidiary Body on Scientific, Technical and Technological Advice

[SBSTTA] of the CBD) as well as regular meetings of parties where evidence-based decision making requires observation and understanding of the global marine system.

Convention/Agreement	A	B	C	D	E	F	G	H	I	J	K
1. IWC	Yes	Yes		Yes		Yes					
2.Convention on fishing	Yes									Yes	
3. Convention on high seas oil casualties								Yes		Yes	
4. Ramsar	Yes	Yes	Yes	Yes		Yes				Yes	Yes
5. Dumping convention						Yes		Yes		Yes	Yes
6.Heritage Convention			Yes	Yes						Yes	Yes
7. CITES	Yes	Yes				Yes				Yes	
8. Marine pollution (not oil)								Yes		Yes	
9. Marpol						Yes		Yes		Yes	
10. CMS	Yes	Yes	Yes	Yes		Yes				Yes	
11. UNCLOS	Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes	Yes
12. Basel						Yes		Yes		Yes	Yes
13. CBD	Yes	Yes	Yes	Yes		Yes	Yes		Yes	Yes	Yes
14. High seas fisheries compliance	Yes									Yes	Yes
15. Part XI UNCLOS							Yes			Yes	Yes
16. Straddling stocks agreement	Yes	Yes			Yes	Yes		Yes		Yes	Yes
17. Protocol marine pollution					Yes	Yes	Yes	Yes		Yes	Yes
18. Cartegena							Yes		Yes	Yes	Yes
19. Stockholm						Yes	Yes	Yes		Yes	Yes
20. Antifouling					Yes	Yes	Yes	Yes		Yes	
21. Ballast						Yes	Yes		Yes	Yes	Yes
22. Port state measures	Yes									Yes	Yes
23. Nagoya	Yes	Yes	Yes							Yes	Yes

Table 2.1. The requirements of 23 International Conventions and Agreements: A. Sustainable management of living resources; B. Sustainable management of unexploited species; C. Habitat management or protection; D. Implement protected areas; E. Precautionary principle; F. Monitoring of species, habitats or environment; G. Environmental impact assessment; H. Prevention of environmental pollution; I. Biosecurity; J. Encourage or impel international cooperation; K. Capacity building. The full names of the Conventions and Agreements are as follows: (1) International Whaling Convention (1946); (2) Convention on Fishing and Conservation of the Living Resources of the High Seas (1958); (3) International Convention Relating to Intervention on the High Seas in Cases of Oil Pollution Casualties (1969); (4) Convention on Wetlands of International Importance Especially as Waterfowl Habitat (Ramsar; 1971); (5) Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972); (6) Convention Concerning the Protection of the World Cultural and Natural Heritage (1972); (7) Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES; 1973); (8) Protocol Relating to Intervention on the High Seas in Cases of Marine Pollution by Substances Other than Oil (1973); (9) Protocol of 1978 Relating to the International Convention for the Prevention of Pollution from Ships, 1973, (Marpol); (10) Convention on the Conservation of Migratory Species of Wild Animals (CMS or Bonn Convention; 1979); (11) United Nations Convention on the Law of the Sea (UNCLOS; 1982); (12) Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (1989); (13) Convention on Biological Diversity (CBD; 1992); (14) Agreement to Promote Compliance with International Conservation and Management Measures by Fishing Vessels on the High Seas (1993); (15) Agreement Relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982 (1994); (16) Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (1995); (17) Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (1996); (18) Cartegena Protocol on Biosafety to the Convention on Biological Diversity (2000); (19) Stockholm Convention on Persistent Organic Pollutants (2001); (20) International Convention on the Control of Harmful Anti-Fouling Systems on Ships (2001); (21) International Convention for the Control and Management of Ships' Ballast Water and Sediments (2004); (22) Agreement on Port State Measures to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing (2009); (23) Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from Their Utilization to the Convention on Biodiversity (2010).

As a member of the United Nations, the UK is also a signatory to the Sustainable Development Goals and the 2030 Agenda, including SDG 14: Life Below Water and its 10 Targets.

- By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution.
- By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and acting for their restoration in order to achieve a healthy and productive ocean.
- Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels.
- By 2020, effectively regulate harvesting and end overfishing, illegal, unreported and unregulated fishing and destructive fishing practices and implement science-based management plans, in order to restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield, as determined by their biological characteristics.
- By 2020, conserve at least 10% of coastal and marine areas, consistent with national and international law and based on the best available scientific information.
- By 2020, prohibit certain forms of fisheries subsidies which contribute to overcapacity and overfishing, eliminate subsidies that contribute to illegal, unreported and unregulated fishing, and refrain from introducing new such subsidies, recognizing that appropriate and effective special and differential treatment for developing and Least Developed Countries (LDCs) should be an integral part of the World Trade Organization fisheries subsidies negotiation.
- By 2030, increase the economic benefits to Small Island Developing States (SIDS) and LDCs from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture and tourism.
- Increase scientific knowledge, develop research capacity and transfer marine technology, taking into account the Intergovernmental Oceanographic Commission Criteria and Guidelines on the Transfer of Marine Technology, in order to improve ocean health and to enhance the contribution of marine biodiversity to the development of developing countries, in particular SIDS and LDCs.
- Provide access for small-scale artisanal fishers to marine resources and markets.
- Enhance the conservation and sustainable use of oceans and their resources by implementing international law as reflected in UNCLOS, which provides the legal framework for the conservation and sustainable use of oceans and their resources, as recalled in paragraph 158 of 'The future we want'.

The CBD, to which the UK is a signatory, has also agreed the Kunming-Montreal Global Biodiversity Framework, which has 23 action-oriented global targets (CBD Secretariat, 2024) for urgent action over the decade to 2030:

1. Plan and manage all areas to reduce biodiversity loss.
2. Restore 30% of all degraded ecosystems.
3. Conserve 30% of land, waters and seas.
4. Halt species extinction, protect genetic diversity, and manage human-wildlife conflicts.
5. Ensure sustainable, safe and legal harvesting and trade of wild species.
6. Reduce the introduction of invasive alien species by 50% and minimize their impact.
7. Reduce pollution to levels that are not harmful to biodiversity.
8. Minimize the impacts of climate change on biodiversity and build resilience.
9. Manage wild species sustainably to benefit people.

10. Enhance biodiversity and sustainability in agriculture, aquaculture, fisheries, and forestry.
11. Restore, maintain and enhance nature's contributions to people.
12. Enhance green spaces and urban planning for human well-being and biodiversity.
13. Increase the sharing of benefits from genetic resources, digital sequence information and traditional knowledge.
14. Integrate biodiversity in decision-making at every level.
15. Ensure that businesses assess, disclose and reduce biodiversity-related risks and negative impacts.
16. Enable sustainable consumption choices to reduce waste and overconsumption.
17. Strengthen biosafety and distribute the benefits of biotechnology.
18. Reduce harmful incentives by at least $500 billion per year and scale up positive incentives for biodiversity.
19. Mobilize $200 billion per year for biodiversity from all sources, including $30 billion through international finance.
20. Strengthen capacity-building, technology transfer, and scientific and technical cooperation for biodiversity.
21. Ensure that knowledge is available and accessible to guide biodiversity action.
22. Ensure participation in decision-making and access to justice and information related to biodiversity for all.
23. Ensure gender equality and a gender-responsive approach for biodiversity action.

For the United Nations Framework Convention on Climate Change (UNFCCC), the United Kingdom has agreed to reduce its greenhouse gas emissions by 100% by 2050 compared to 1990 levels (the Net-Zero Emissions target). This will be achieved through the Nationally Determined Contributions (NDCs) that the UK submits to the UNFCCC. Not only does science play a critical role in the monitoring of emissions, but increasingly it is contributing to knowledge about blue carbon ecosystems and marine carbon dioxide removal (mCDR). NERC/UKRI has also undertaken to significantly reduce its CO_2 footprint as part of the UK Net Zero emissions strategy.

As well as international agreements, the UK is a signatory of regional agreements such as the Oslo Paris Convention (OSPAR) which commits 15 countries to cooperate in the protection of the environment of the northeast Atlantic. There are also regional implementing bodies such as the RFMOs where countries cooperate to sustainably manage fisheries. RFMOs rely on data-driven models to ensure that fish stocks are not overexploited, and other scientific knowledge to mitigate broader ecosystem impacts of fishing. Increasingly, they are having to consider science input on climate change effects on fisheries and their ecosystems. RFMOs can be supported by science advisory bodies, such as the International Council for the Exploration of the Sea (ICES), which receive significant input from the UK marine science community. The UK is currently a contracting party to five RFMOs including: International Commission for the Conservation of Atlantic Tunas (ICCAT), Indian Ocean Tuna Commission (IOTC), Northwest Atlantic Fisheries Organisation (NAFO), North Atlantic Salmon Conservation Organisation (NASCO), and Northeast Atlantic Fisheries Commission (NEAFC). It is also a contracting party to the Convention for Conservation of Antarctic Marine Living Resources (CCAMLR) which assumes many of the functions of an RFMO in the Southern Ocean.

2.3. UK Marine Science

As outlined above (section 1.1) the UK is an established leader in marine science, drawing on a strong and diverse marine science institutional landscape, comprising:

- UK marine science Institutes supporting national capability including facilities and research: the National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML), The Marine Biological Association of the UK (MBA), British Antarctic Survey (BAS), Scottish Association for Marine Science (SAMS), the Sea Mammal Research Unit (SMRU).
- Higher Education Institutes: Several universities such as Southampton, Liverpool, Newcastle, Plymouth, Bangor, St Andrews, Edinburgh, Heriot-Watt, and the University of Highlands and Islands have specific marine science departments including marine research stations and, in some cases, inshore / coastal research vessels. Many more universities are involved in aspects of broader marine science and related Earth system science, environmental science, marine engineering, climate research, ocean circulation, the cryosphere, ocean-climate modelling, biodiversity, conservation and policy (e.g. Universities of Aberdeen, Bournemouth, Bristol, Cambridge, Cardiff, East Anglia, Essex, Exeter, Hull, Imperial, Leeds, Manchester, Oxford, OU, Portsmouth, Reading, Strathclyde, Swansea, UCL).
- Defra and its executive agencies (e.g. Centre for Environment, Fisheries and Aquaculture Science [Cefas], The Environment Agency, The Marine Management Organisation [MMO], Natural England and the Joint Nature Conservation Committee [JNCC]) and the equivalent bodies in devolved administrations.
- Museums and other collections which have an important role in biodiversity research, as well as taxonomic and evolutionary science related to the ocean, including through the use of marine organisms for fundamental biological science (e.g. the Natural History Museum, London).
- Non-Governmental Organisations (e.g. the Zoological Society of London [ZSL], World Wildlife Fund for Nature [WWF], Flora and Fauna International [FFI], the Shark Trust, Marine Conservation Society of the UK [MCS]).

As previously mentioned, UK marine science outputs generate more academic impact than any other nation. Further evidence is provided by the Research Excellence Framework (REF), the UK's system for assessing the quality of research, which acknowledges the amount of world-leading (4*) research in marine science from UK marine sciences (for example, Southampton (62%), Bangor (48%), Liverpool (44%), UHI (33%), Plymouth (23%). Notable examples of REF impact case studies which were categorised as world leading (4*) include:

- 'Rising tide: informing management, planning and policy on acceleration of sea level rise, increased local flooding and changes in tide around the UK and world' led by Southampton.
- 'Government and assessment bodies adapt an innovative quantitative method to assess the suitability of mobile bottom fishing gear' led by Bangor.
- 'Deep impact: engaging public audiences and policy makes with the exploitation and stewardship of biodiversity in the deep ocean' led by Southampton.
- 'Enhancing the protection of marine ecosystems in the UK and globally' led by York.
- 'Research on the ecological impacts of plastics in the marine environment' led by Exeter.

The UK Government spends <2% of GDP on research and development but <1% of this funding is invested in marine science (IOC-UNESCO, 2020). The world class output volume (3rd at 10% in terms of total publications after US and China) and quality (1st globally in category normalised citation impact) of UK marine science is thus a very high return on investment. Moreover, funding grew significantly between 2013 - 2017 and the UK is still amongst the top 10 countries globally in terms of marine science personnel. This can be set against a global picture of increasing marine science publications (40,000 – >116,000 from 2000-2017) as well as an increasing global trend towards international collaboration, with UK marine scientists playing an important role in international science programmes, with 80% of outputs involving international collaborations (globally joint highest with German). The UK has particular strength in ocean-climate research, but all areas of marine science are internationally competitive. There is a strategic focus on the Atlantic Ocean, pole to pole through major research programmes, such as the National Capability AtlantiS programme, and the UK continues to lead major components of the sustained observing system in the Atlantic through the RAPID/OSNAP mooring arrays to measure basin scale transports and GO-SHIP repeat hydrographic survey lines. However, UK marine science fields have a broad geographical range which operates in all oceans including polar, temperate and tropical latitudes, and from coastal to deep-sea, and all sub-seafloor environments. In 2024 alone, many remarkable and important discoveries were made by UK marine scientists including:

- Observations of a record loss of Antarctic Sea ice in 2023 (Josey *et al.*, 2024).
- A link between freshwater anomalies in the North Atlantic in winter and warmer, drier summers in Europe (Oltmanns *et al.*, 2024).
- The discovery of controls on the storage of carbon in marine sediments, a globally important sink of CO_2.
- The discovery that marine algae are important sources of climate cooling gases (Wang *et al.*, 2024).
- The discovery that ferro-manganese nodules in the deep sea may produce oxygen (Sweetman *et al.*, 2024).

Because of the strength of UK marine science, it is the lead or a leading contributor to a wide range of important international marine science programmes including:

- **Seabed 2030**, an international mission to map the ocean floor by 2030.
- **Challenger 150**, an international programme researching biodiversity in the deep sea.
- **Ocean Census**, a programme aimed at accelerating species discovery in the ocean.
- **Nutrient Pollution – Global Action Network**, a global programme aimed at addressing nutrient and wastewater pollution impacts on ocean ecosystems and human health.
- **Global Ocean Decade Programme for Blue Carbon** aimed at generating new knowledge and solutions to mitigate the effects of climate change.
- **Ocean Biomolecular Observing Network (OBON)**, aimed at developing a global ocean observation network for marine life based on molecules like DNA for sensing of ocean health and improved management of human activities influencing the ocean.
- **Ocean Acidification Research for Sustainability (OARS)** a programme aimed at global monitoring of ocean acidification and its effects on marine life.
- **Joint Exploration of the Twilight Zone Ocean Network (JETZON)** a programme aimed at better understanding of the mesopelagic zone (200-1,000m) and human impacts on it.

- **ForeSea – The Ocean Prediction Capacity of the Future** aimed at improving the science, capacity and efficiency of ocean prediction systems for economic and societal benefit.
- **International Ocean Drilling Programme (IODP[3])** - an international marine research collaboration that explores Earth's history and dynamics using ocean-going research platforms, to recover data recorded in seafloor sediments and rocks, and to monitor subseafloor environments.
- **GEOTRACES** - an international programme which aims to improve the understanding of biogeochemical cycles and large-scale distribution of trace elements and their isotopes in the marine environment.

UK marine scientists also contribute knowledge and scientific evidence to critical intergovernmental programmes including: the Intergovernmental Panel on Climate Change (IPCC); the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES); the IOC-UNESCO UN Decade of Ocean Science for Sustainable Development and support the UK Government's input into the international treaties and agreements outlined above, including through training activities that build marine science capacity in developing countries. UK ocean observations contribute to increasingly accurate weather forecasting, nationally and internationally, and to longer-term prediction of changes in the ocean relating to CO_2 emissions, including sea level rise, long term trends in storm frequency and strength, and how warming, deoxygenation and acidification influence marine life, including fisheries and aquaculture species. This body of information forms the major contribution to development of up-to-date advice to the UK government and, internationally, through the Marine Climate Change Impacts Partnership (MCCIP). UK ocean observations also contribute to prediction of marine hazards and development of mitigation and adaptation strategies to prevent loss of human life and infrastructure. Increasingly, marine science is contributing to technology development and patents including (from Blasiak *et al.*, 2020):

- New pharmaceuticals, nutraceuticals and cosmeceuticals
- Technologies for mitigating or adapting to climate change
- Improvements in technology for ships and other vessels (e.g. autonomous underwater and surface vehicles)
- Better ways to measure and test physicochemical properties of seawater
- Improvements in the sustainability of aquaculture and fisheries
- Improvements in treatment of water, wastewater, sewage and sludge
- Hydraulic engineering and civil engineering
- Improvements in food technology
- Drilling and mining
- Computing and data technology
- Mechanical engineering

It can therefore be seen that UK marine science provides critical knowledge that benefits society, enabling it to adapt to and mitigate environmental change, to develop a sustainable and competitive blue economy and to maintain health and well-being.

2.4. The Current Portfolio of UKRI/NERC Funded Science Utilising the Marine Research Infrastructure

The range and breadth of the research facilitated by UKRI/NERC marine research infrastructure can be appreciated through consideration of some of the current, major NERC-funded programmes. These provide an indicator of the status and approach of UK marine and associated Earth system science. Current programmes reflect an ongoing trend towards interdisciplinary science and greater focus on taking the steps to ensure that science excellence informs solutions for society, by bringing together observations and digital tools along with cross disciplinary expertise.

Large scale programmes, such as those funded as national capability science, are developed to be aligned with UK national socioeconomic and strategic priorities, leveraging international programmes and partners to optimise the impact of combined investment. Conversely, the majority of discovery science programmes undertake curiosity-driven research which, in many cases, still results in key contributions to society, albeit sometimes less direct/immediate. In relation to national capability, the Atlantic Climate and Environment Strategic Science (AtlantiS, 2024) programme is a major, large, single-centre, five-year science programme which replaces Climate Linked Atlantic Sector Science (CLASS, 2018). The overarching goal of AtlantiS is to support the creation of healthy, diverse, and resilient marine environments, sustainable blue economies, and communities safe from natural hazards. The programme underpins large-scale sustained observations and modelling programmes, technological development, and digital innovation as well as an integrated research programme. The programme is aligned with UK science priorities, UKRI and NERC strategies, national and international frameworks, strategies and implementation plans, including for the UN Ocean Decade, the Global Ocean Observing System (GOOS), IPCC, MCCIP, and the National Adaptation Programme, with a strengthened focus on delivering information to support decision making, whilst addressing priority knowledge gaps. Priorities include:

- Understanding natural and human-induced changes in the Atlantic ecosystem.
- Understanding the connectivity between the ocean, shelves, and coasts, and the impacts of climate mitigation strategies.
- Determining the ocean's capacity to continue mitigating climate change by absorbing heat and carbon.

The sustained observations funded under AtlantiS comprise a large component of the UK's contributions to GOOS, guided by the recommendations in the SSOOP report (Figure 2.1).

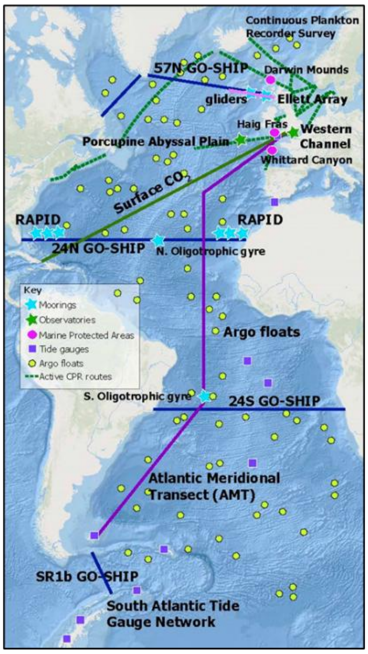

Figure 2.1: Sustained ocean observation components funded under AtlantiS including: GO-SHIP repeat hydrographic lines (SR1B and A09.5); Atlantic Meridional Transect (AMT); Deepwater mooring arrays: RAPID and Ellett across the North Atlantic; Glider transects along the Ellett Array; PAP-SO and Western Channel Observatory (WCO) timeseries; SOOP Continuous Plankton Recorder (CPR) surveys; Surveys of Marine Protected Areas (MPAs): Haig Fras, Whittard Canyon and Darwin Mounds; Data and product development; Marine meteorology (humidity and flux parameters); Annual State of Sea Level report, tide gauge datasets; Biogeochemical and Deep Argo Float Datasets; Underway surface CO_2.

Complementary to AtlantiS, two programmes, National Capability Science programme BIOPOLE (BIOPOLE, 2023) and the strategic priority programme BIO-Carbon (BIO-Carbon, 2022), have a strong interdisciplinary focus to advance understanding of physical, chemical and biological processes governing the ocean system. Programmes such as BIO-Carbon and BIOPOLE require interdisciplinary science demanding simultaneous physical, chemical and biological observations at a range of spatial and temporal scales, and model complex ecosystem processes and their interactions (see section 9.3 for more details). BIO-Carbon is also part of the international UN Ocean Decade programme Joint Exploration of the Twilight Zone Ocean Network (JETZON).

NERC also funds strategic research through so called highlight topic grants addressing one of a defined list of strategic topics driven by the marine science community. Examples include:

- ArctiConnect
- ESweets
- Effect of trawling on blue carbon
- Storm impact of gravel beaches

Strategic research funding includes strategic programmes which are major activities that address complex science questions in which the research is expected to be large-scale and complex, and logistically challenging or there are significant opportunities for partnership development. Examples of strategic programmes where marine science is important include:

- Aquaculture research collaborative hub UK (ARCH-UK)
    - A programme to foster collaboration between researchers and business to identify and develop new approaches to solving major research challenges and deliver key benefits to the UK aquaculture sector
- Biological influence on future ocean storage of carbon (BIO-Carbon)
    - A programme to provide new insights into the role of marine life in ocean carbon storage and robust predictions of future ocean carbon storage in a changing climate.

- Ecological consequences of offshore wind (ECOWind)
    - A programme that addresses how offshore wind expansion, combined with other anthropogenic pressures, affects species interactions and marine ecosystems. It also aims to understand how these consequences enable robust approaches to marine environmental restoration and net environmental gain.
- Ecological effects of floating offshore wind (ECOFLOW)
    - A programme to support and fund research that will further our understanding of how marine ecosystems will respond to the planned large-scale expansion of floating offshore wind infrastructure usage in UK waters.
- Influence of man-made structures in the ecosystem (INSITE)
    - A programme to increase understanding of the impact that man-made structures such as oil and gas rigs and offshore wind farms have on the North Sea ecosystem. It will provide robust scientific evidence to inform environmental management strategies for future decommissioning.

All these programmes are designed to provide the evidence to support marine industries in partnership with industry groups.

NERC also funds strategic programmes in partnership with other funding agencies and these are often focused on bringing knowledge and tools together to support decision making. For example, the Sustainable Management of Marine Resources (SMMR) Programme (SMMR, 2020) is funded by NERC, the Economic and Social Research Council (ESRC) in partnership with Defra and Marine Scotland. The goal is to build science and policy and integrate disciplines to support decision-making within the UK Exclusive Economic Zone. The programme addresses critical marine research, management and engagement gaps in areas such as natural capital to ocean literacy, and systems-based management.

The NERC-funded strategic programme Seabed Mining and Resilience to Experimental Impact (SMARTEX, 2021), is another example strategic programme with academic, industry and government partners. It aims to better understand the ecosystem in the Pacific abyss, a target for marine mining, and how the different components interact and interconnect. Ultimately, it aims to build a range of mathematical models to predict the impacts of deep-sea mining at larger spatial and temporal scales. SMARTEX involves a partnership between the National Oceanography Centre, the Natural History Museum, the British Geological Survey, several universities (Heriot-Watt, Liverpool, Plymouth and Southampton), the Joint Nature Conservation Committee as well as NORCE in Norway, the Senckenberg Museum in Germany and an industrial partner, UK Seabed Resources Ltd.

Defra's flagship Marine Natural Capital Ecosystem Assessment programme (Szylarski, 2022) has highlighted Defra's evolving requirements for observation and prediction of the extent, condition and change over time of England's marine ecosystems and natural capital, and the benefits to society. This has stimulated collaborations with NERC and other parts of UKRI, highlighting opportunities for greater collaboration in marine observation and associated digital environment into the future. With Innovate UK (UKRI), the Marine Natural Capital and Ecosystem Assessment Programme (mNCEA) has delivered a grant funding competition inviting small-medium sized enterprises (SMEs) to bid to enhance their innovative technologies and end-to-end marine monitoring systems to improve observation capabilities of biodiversity in UK waters. Defra also sponsored FMRI's workshop on biological and biogeochemical sensor priorities. This sponsorship was indicative of FMRI and Defra's shared priorities in the marine monitoring and observing space – recognising the value in sensor development as an enabler of innovative data collection in the marine environment. The workshop led to publication of a report (Mowlem and Allen, 2024), co-authored between NOC and Defra, to inform the 'FMRI: Accelerating adoption of marine sensor innovation' UKRI funding opportunity (UKRI, 2024).

In driving the development of innovative digital solutions, Twinning Capability for the Natural Environment (TWINE) is a partnership between NERC and the Met Office. The digital twin pilot projects will demonstrate how research, using Earth observation data and emerging digital twinning technologies, can transform environmental science across priority areas including climate change, biodiversity and ecosystems, and natural hazards.

TWINE includes three projects of relevance to FMRI:

- SyncED-Ocean: Coastal ocean ecosystems for assimilation to marine system models.
- MAS-DT: Ocean glider observations for ocean models which underpin weather forecasts.
- Splash: Analysing wave overtopping to produce a warning tool for wave hazards.

The formation of the Advanced Research and Invention Agency (ARIA) is creating new opportunities for innovative, forward-looking research on high impact topics. One example is the ARIA Call on Forecasting Tipping Points (Bale and Bohndiek, 2024) which is focused on bringing together climate measurements and models to create an early warning system. Twenty-seven projects, backed by £81m, have now been funded under this call within three technical areas: 'designing an affordable, sustainable, and just sensing system; deploying new and existing sensing systems in the Greenland Ice Sheet and Subpolar Gyre; and developing new modelling methods'.

A substantial volume of UK marine and associated Earth system science is also funded through NERC discovery science grants. Four grant types are available:

- Pushing the Frontiers grants – Maximum of £1 million per award.
- Exploring the Frontiers grants – Maximum of £100,000 per award.
- Large grants – £1.2-3.7 million per award.
- Urgency funding – Maximum of £100,000 per award.
- Independent research fellowships.

These opportunities fund a range of activities from small grants that allow researchers to explore and test new ideas, approaches and technologies (Exploring the Frontiers) to larger grants aimed at curiosity-driven, high-risk, high-reward projects that lead to scientific discoveries that are likely to change the future landscape of a discipline (Pushing the Frontiers). All these funding types may use marine infrastructure. Urgency funding is a fast-track route to take advantage of short-lived and unexpected research opportunities (e.g. earthquakes, sudden ecosystem change). Independent research fellowships are aimed at funding early career researchers who have a Ph.D. and wish to develop an independent research project, helping researchers to develop the potential to become research leaders of the future.

Examples of current active marine science grant awards from NERC include:

- A deep-sea perspective on coral resilience in a changing world.
- A MISSING LINK between continental shelves and the deep sea: Addressing the overlooked role of land-detached submarine canyons.

- Can you hear marine snow falling?
- ASIMOV: Autonomous Sensors for fast *In-situ* Measurements of nutrient biogeochemical essential Ocean Variables.
- Co-evolution of phytoplankton dynamics and environment at the Fram Strait.
- Aggregation, production and spillover: the cumulative effect of man-made offshore structures on fish.
- ASYNC: Resolving asynchronous responses of North Atlantic climate to deglacial changes in ocean circulation.
- Nitrogen fixation in the Arctic Ocean.
- Observations and synthesis to establish variability and trends of oceanic pH.
- PARTITRICS: PARTIcle Transformation and Respiration Influence on ocean Carbon Storage.
- ReSOW: Recovery of Seagrass for Ocean Wealth UK.
- SEANA: Shipping Emissions in the Arctic and North Atlantic atmosphere.

NERC also funds Ph.D. studentships in marine science through several routes. These include Doctoral Landscape Awards aimed at training the next generation of researchers in environmental sciences mainly at universities, which effectively replace the previous Doctoral Training Partnerships (DTPs). There are also Doctoral Focal Awards which provide funding for research training in specific, tightly focused themes or challenges and replace the previous Centres for Doctoral Training (CDTs) several of which were marine focused e.g.:

- SMMR: Sustainable management of UK marine resources.
- IDCORE: Industrial CDT in Offshore Renewable Energy.
- Aura CDT: Training in offshore wind energy.

It is important to note that many of these NERC funding streams and their funded projects are supported by UKRI/NERC marine infrastructure including ships, autonomous platforms and digital infrastructure.

2.5. Externally Funded Science Programmes and Marine Infrastructure

UK scientists are still able to participate in the EU – Horizon 2020 funding programme. UK marine scientists are involved in coordinating or participating in a number of Horizon 2020 projects. Examples of these include:

- MACOBIOS: a programme exploring the impacts of climate change on biodiversity and ecosystem services as well as societal vulnerabilities to changes and the potential of nature-based solutions (University of Portsmouth).
- Ocean ICU: Improving Carbon Understanding aimed at gaining a new understanding of the biological carbon pump and its processes, relevance to human activities such as fishing and mining and development of approaches to minimise the effects of such activities on the carbon cycle (Plymouth Marine Laboratory).
- SEAO$_2$-CDR: Strategies for the Evaluation and Assessment of Ocean based Carbon Dioxide Removal a project aimed at understanding of the effects, benefits, and feasibility of capturing carbon dioxide (CO_2) from the atmosphere and storing it in the ocean (National Oceanography Centre).

- REDUCE (Reducing bycatch of threatened megafauna in the East Central Atlantic) is aimed at undertaking research to reduce the fisheries bycatch of threatened marine species such as birds, turtles, cetaceans, sharks and rays (Marine Biological Association of the UK).
- Ocean-Cryosphere Exchanges in Antarctica (OCEAN): Impacts on Climate and the Earth System will undertake observations and develop numerical models to improve predictions of how changes in the Antarctic and Greenland ice sheets impact global climate (British Antarctic Survey, University of Northumbria, University of Liverpool).

These projects (and others) not only involve UK scientific expertise but also require UK marine science infrastructure for ocean observations, seafloor and sub-seafloor experiments and modelling. They also access wider marine infrastructure across Europe funded by other EU states. The Ocean Facilities Exchange Group (OFEG, 1996) is a European organisation which enables exchange of vessels in the European Global and Ocean Class research fleet through barter arrangements as well as facilitating cooperation amongst research vessel operators.

Philanthropic funding of marine scientific research is becoming more important for UK scientists, especially in geoscience and biodiversity research. This support comes in different forms, mainly in the shape of direct funding (e.g. The Nippon Foundation Seabed 2030, Ocean Census and Ocean Voices programmes) but also, increasingly in provision of major marine infrastructure for ocean research including Ocean Class Research Vessels, autonomous platforms, remotely operated vehicles (ROVs) and submersibles. An example of these organisations and their facilities include the Schmidt Ocean Institute (SOI) who currently operate the 110 m R/V *Falkor (too)* (Schmidt Ocean Institute, 2024) which is equipped with multibeam echosounders, the ROV SuBastian, eight on-board laboratories and a range of other equipment. Another example is the Norwegian not-for-profit REV Ocean which is in the final stages of construction of the 190 m REV *Ocean* vessel which will be equipped with multibeam sonar, ROV *Aurora*, the submersible *Aurelia*, a helicopter, a trawl system, CTD rosette and winch, SCUBA and technical diving facilities and a range of laboratories, meeting rooms and a lecture theatre (REV Ocean, 2025). These vessels are offered based on free access to the ship and all equipment but do not cover research costs, both during and after expeditions (e.g. chemical consumables, post expedition laboratory studies etc). In some cases, philanthropic funding has enabled research which has not been achievable financially, or with national infrastructure (e.g. exploration of all the world's deepest ocean trenches during the Five Deeps expedition led by UK scientists (Caladan Oceanic, 2018). Whilst using philanthropic marine science infrastructure can be more complicated than using national facilities, it is increasingly becoming a viable route to access, for example, remote deep-sea systems which are expensive and difficult to explore using national infrastructure.

2.6. Recent Reviews of Requirements for UK Marine Infrastructure

In part, the UK has maintained a strong, internationally competitive position in marine science because it has invested heavily in research infrastructure over the years, as outlined in the 'Scanning the Horizon' report (Kennedy and Liss, 2013). Thus, UK marine scientists are relatively well equipped with the infrastructure to support cutting edge globally leading science, with modern multipurpose research vessels and autonomous technologies, comprising off-the-shelf equipment such as gliders, as well as bespoke examples such as the Autonomous Long Range (ALR) vehicles.

The NZOC WP1 Report on Future Science Needs highlighted that the UK's long-standing record in marine science is reliant on research vessels and ship-based equipment as the current most reliable and accurate means of carrying out marine science. The report also noted that the recent expansion in Marine Autonomous Systems (MAS) and Earth Observation (EO) has opened new avenues for research and revolutionised our understanding of the ocean. NZOC WP1 conducted a survey of usage of the National Marine Facility (NMF) in recent years, showing a wide range in subject areas but increasing strengths in multidisciplinary research, and finding that over 75% of respondents used autonomous technology in their research. The UK has adapted to using autonomous vehicles much more rapidly than the global average (Brannigan, 2021). For example, over the last five years, the UK has been publishing results based on gliders at 2-3 times the rate of the global average. This UK capability has been featured in several European Marine Board (EMB) reports on future research vessels (Rogers *et al.*, 2015). Key positive disrupters to our observation capability include the Argo array of profiling floats and satellite altimetry (most recently swath altimetry). It is anticipated that further step changes will be made in biogeochemistry with the expansion of autonomous observations and sensing capabilities. However, the real power is the value that can be extracted by combining these observations (further discussed in section 10.5).

The NZOC WP1 report also emphasised that '*while an ever-increasing number of UK marine scientists are using autonomous technologies and low-cost options, a number of fields are unlikely to be achievable through net zero approaches within 15 years.*'

Examples of these fields of research include:

- Deep rock drilling and sediment coring.
- Marine ecosystem studies with measurements of rates of production and respiration.
- Measurements of isotope systems.
- Sampling of marine organisms from deep benthic and pelagic environments for studies of biodiversity and ecosystem structure and function.
- Manipulative seafloor experiments.

In addition, the data returned from ships are of the highest accuracy, being calibrated using laboratory analyses and international reference materials, and enable many variables to be measured at the same time and place, ensuring maximum value is extracted from data-streams collected from more autonomous systems. Moreover, a key driver of scientific innovation and discovery is the development of new technologies, methods and observational tools. Within marine and associated Earth system science, many of these advances necessitate extensive development and testing of new methods with direct human involvement within the intended deployment environment (i.e. at sea). Ensuring delivery of maximum data, information, knowledge and understanding value for investment in observation capability, and maintaining a pipeline for innovation, is at the core of the vision for FMRI. Further details of the NZOC recommendations are highlighted in chapters 10, 11 and 12 below.

In 2022, a consultation with the UK marine science community was held on prioritising UK sustained ocean observations (NERC-UKRI, 2022). The review highlighted that the observing systems are of immense scientific value and should be continued. In particular, the review panel noted:

- *'Comparison across the different sustained observations is not possible due to the specialist nature, hence there was a concern about an 'apples-and-pears' comparison.*

- *The societal benefit, specific purpose and science questions addressed should be articulated more clearly and more visibly (and preferably collated in one place) for non-specialist audiences.*
- *For several observing systems, data should be readily accessible in a timely way and comply with FAIR (findable, accessible, interoperable, reusable) principles.*
- *There should be a more integrated and cross 'systems view' across all observing systems e.g., different systems contribute in different ways to building a picture and reducing uncertainties in the state of inventories and fluxes of carbon (this is an observation both about the UK contributions and the international systems as a whole).*
- *Common success metrics should be developed for benefits from the observing systems e.g., for uptake of available data, training, capacity development and innovation.*
- *Opportunities for transformation in these observations through technological and other innovations should be identified and plans/roadmaps to achieve these developed.'*

These recommendations are featured in this document to help frame requirements for FMRI which comprises both sustained and experimental capabilities. In particular, the science requirements are framed under marine science 'Grand Challenges' to ensure the societal benefit, purpose and science questions are clear, and to provide an integrated cross systems view of observation requirements with contributions of capabilities articulated.

2.7. Expected Future Priorities for Marine Science

Looking to the future, while NERC is coming to the end of its current strategic planning period, it is likely to continue to reinforce a focus on science for solutions for society. NERC's Strategic Delivery Plan 2022-2025 (NERC, 2022b) highlights the importance of delivering world- class impacts: *'The expertise of our research community ensures robust, evidence-led policymaking relating to the environment. By diagnosing harm to the environment and human health, our science informs policymakers and the public of the need for change and guides effective interventions. We provide the insight and predictive power for the public and private sectors to understand and mitigate environmental risks globally. Our work underpins management of natural capital and the protection and restoration of biodiversity in the face of human activity. In partnerships which include engineers, social scientists, biologists, and economists, among others, NERC working across UKRI can help society to adapt our lives and livelihoods to a changing climate both in the UK and across the globe.'* Furthermore, focus on research aligned with UK policy priorities (see above), working in partnership with other research councils, government and industry partners is expected to grow as a priority into the future. The UK National Climate Science Partnership (UKNCSP; Met Office, 2021), a collaboration between the NERC funded centres and the UK Met Office, is a recent example. This direction reinforces the need to consider FMRI in the wider national partnerships landscape.

The NZOC WP1 report noted: '*Persistent and emerging drivers for marine research include the need for new understanding of the ocean's role in climate, the existence of climate tipping points and how near we may be to reaching them, the responses of polar regions and deep seas to climate change, and feedbacks between the polar and global oceans, between the oceans and atmosphere, the oceans and cryosphere, and between physical ocean changes and ecosystem change. The importance of understanding the interaction between the open ocean and coasts has also been highlighted, especially in the face of a changing climate, where the increase in extreme weather events, storminess and regional sea level changes has been* *demonstrated to impact on society. New questions are also arising with the advent of improvements in sensing technology, surrounding carbon and nutrient cycling, conservation management and ocean health, and geohazards and risk management. These science drivers are just a few of the topics currently funded by the UK NERC, and their relevance is unlikely to diminish in the near future. Scientific research efforts have focused on understanding key processes, improving their representation in numerical simulations of the oceans and climate, and better predicting their likely evolution in the future – with ramifications for society and the blue economy, especially for topics in the coastal regions, or whether weather changes are anticipated.'*

The NERC strategic objective on 'World Class Innovation' highlights the need to '*realise the potential of sensing and monitoring technologies, artificial intelligence and digital twinning, autonomous and remote sensing, and high-performance computing to create new information services for research, government and businesses'* – thus reinforcing the FMRI vision for an integrated research infrastructure combining observational and digital infrastructure. The Foresight Future of the Seas Report outlined future changes that are likely to affect UK interests: under technological interests, it highlighted increasing reliance on satellites and data sharing, with new opportunities from autonomy likely to increase our reliance on satellite technology at sea and create a growing market for data-sharing infrastructure. Building on NERC's Strategic Delivery Plan and looking further into the future, NERC's Digital Strategy 2021-2030 (NERC, 2022a; Figure 2.2) provides a strong foundation to guide the development of FMRI's Digital Infrastructure.

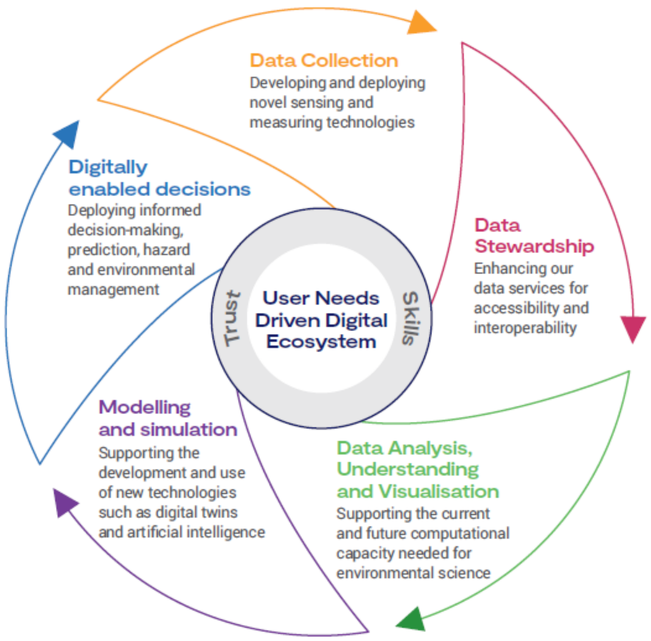

Figure 2.2: NERC's proposed Digital Ecosystem approach bringing together data collection, data stewardship, analysis understanding and visualisation, modelling and simulation for digitally enabled decisions.

To summarise, it is anticipated that the trends we have seen in research focus will continue to be reinforced, such as:

- World class science for solutions and society
- Uniting observations and digital tools
- Working in partnership

3. The Science Requirements Framework: Approach to Identifying Requirements

The Future Marine Research Infrastructure (FMRI) programme sets the challenge of maintaining or enhancing the UK's scientific capability, while achieving both environmentally and economically sustainable operations. This challenge also presents the opportunity to consider holistically the UK's future marine science ambitions and how we can maximise science impact, and information value to society for investment by a) combining a range of observations and digital tools in new and smart ways, and b) advancing partnerships nationally and internationally to deliver a more integrated collaborative capability to deliver to science and society.

In practical terms, the Science Requirements Framework (SRF) will set out, in a step-by-step way, how overarching science goals relate to capability needs, drawing on national strategies and studies to date, and international best practice projecting forward on the timeline to 2040. It will outline the overarching science questions/knowledge gaps and information requirements, consider the underlying phenomena to capture and how this then influences variables/space/time scales, recognising the need for both sustained observations and experimental capabilities, ensuring experimental flexibility to continue to advance innovative science and observe the marine environment and observe other components of the Earth system using marine infrastructure in smarter manner, delivering more value for investment. The SRF will then consider, in general terms, the key capability needs, in order to provide an evidence-based prioritisation of requirements to inform decisions that ensure the best possible outcome for investment into marine science.

The SRF will be used to inform considerations of combined capability options (starting with the business case for investment when the RRS *James Cook* comes to the end of its life) and guide national and international partnerships development. To maximise information value for investment, there is a need to consider individual capabilities as an integrated system to optimise observation synergies, interdependencies, hence provide a framework to consider options, priorities and manage trade-offs.

As outlined in the Figure 3.1, there will need to be a brokering between the requirements and options decision-making, design and implementation as an iterative process. As such, the SRF is expected to be a living document that will develop throughout the FMRI planning and development process.

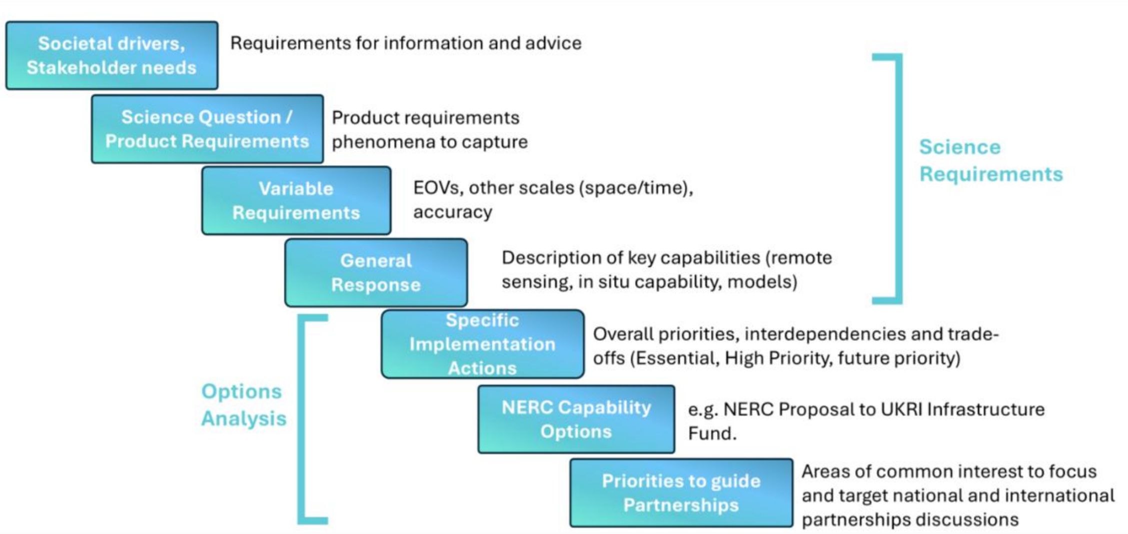

Figure 3.1: Approach to articulating requirements and relationship with options discussions. Adapted from Smith *et al.* (2019).

Drawing on the SRF, NERC will make decisions about where to target investment based on scientific requirements, environmental and economic sustainability, and opportunities to strengthen national and international partnerships. The SRF is therefore part of a package of information which will inform decision making, but it is essential that it reflects the scope and ambition for UK marine science, as well as provide the scientific context for strengthened collaboration nationally (e.g. with the Defra family of organisations and the Met Office) and internationally (e.g. bilaterally other nations with common interests, and through multilateral fora such as the G7 and GOOS).

The SRF will draw on the work of the Net Zero Oceanographic Capability (NZOC) Work Package 1: Future Science Requirements. The work package focused on disciplinary science and the practicalities of delivering science now and into the future. Drawing on the experiences from the UN Ocean Decade, IODP 2050 Science Framework (Koppers and Coggon, 2020) and other national strategies organised around key thematic challenges, the SRF is organised under overarching Marine Science Grand Challenges to organise and elevate ambition in marine science to address society's challenges. The SRF will also consider cross-cutting themes across the Grand Challenges alongside and broader capability requirements which might be necessary to address these.

The SRF highlights the key knowledge gaps and uncertainties within the Grand Challenges to articulate observation requirements that will stretch our capability and drive innovation in how we bring observations and digital tools together. Examples are identified to challenge future marine research infrastructure in different ways – whether that be resolution, remoteness, new methods, techniques and observables, integration across scales, or variables, etc.

At this stage, it helps to articulate some key principles for a future marine research infrastructure:

Principles

Accessible and Impactful – Marine research infrastructure must realise the full societal value and impact of marine data and the scientific information, knowledge and understanding it enables, by creating much wider access to the infrastructure and data, and by increasing the range and accessibility of information and knowledge that comes from it.

Flexible and Responsive – Marine research infrastructure must provide for societal risks and challenges that are prioritised now, and those that will emerge in the future, ensuring that investment continues to maximise opportunities for innovative science and the knowledge it generates.

Integrated and Seamless – Through digital and physical integration, the research infrastructure must provide added value from the diversity of technologies that are needed to meet the challenges of the complexity, hostile nature and sheer scale of the marine environment.

Innovative and Adaptable – Marine research infrastructure must facilitate technological innovation and be adaptable to evolve, using new technologies to provide the data and information required into the future.

Resilient and Collaborative – Marine research infrastructure must have built-in system resilience such that dependencies are robust and prevent single points of failure, that transitions to new technology are smooth and without breakpoints, and that it fully integrates with and adds value to global observing systems and partnerships.

3.1. Stakeholder Engagement

The development of the Science Requirements Framework brought together over 200 people from the science, industry, engineering, policy and beyond (Figure 3.2), including over 60 participants across four UK roadshows in Exeter, London, Liverpool and Edinburgh, and over 60 in five virtual roadshows. This work was supported by a Science Advisory Group across a wide range of scientific disciplines, an editorial board, a specialist geoscience group, an international body of external reviewers, and the Programme Office.

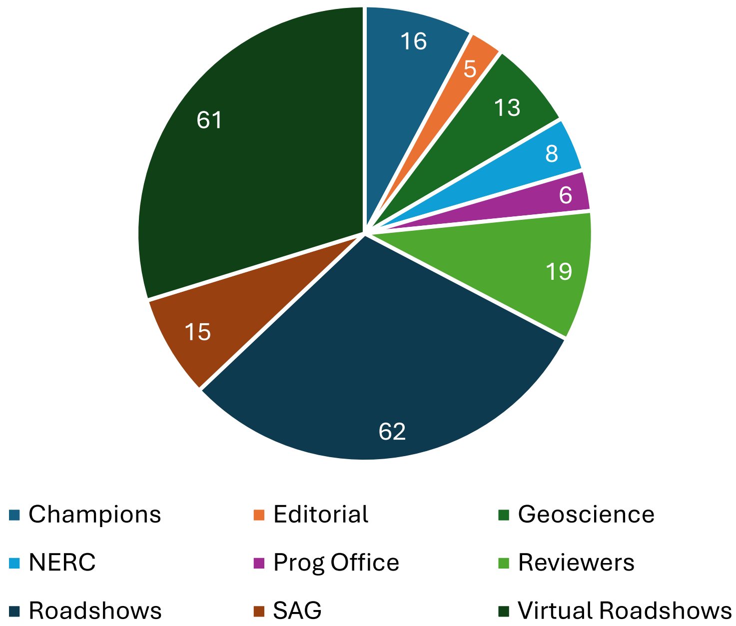

Figure 3.2: Individuals who participated in the FMRI SRF development process.

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PART 2: The Marine Science Grand Challenges

Chapter 4: The Role of the Ocean in a Changing Climate

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4.1. Scope and Context

The ocean plays a central role in the interconnected Earth system which controls planetary climate and habitability. Moreover, multiple processes in the ocean and connected cryospheric, atmospheric, lithospheric and terrestrial system components are highly sensitive to regional and global scale climatic forcing. Consequently, ocean processes can play a major role in climate changes while, reciprocally, changes in the climate system can directly impact marine productivity, biodiversity, resource availability and broader ecosystem services and hazard risks.

4.1.1. Climate Change Signals and Impacts

As a critical component of the global climate system, the ocean plays a major role in regulating climate variability over multiple timescales, including by storing and transporting heat and climate reactive gases (e.g. carbon dioxide, nitrous oxide). Interactions between the ocean, atmosphere, cryosphere and (over long (multi-millennial) timescales) the lithosphere, ultimately determine the average temperature and distribution of heat in the surface Earth system. For example, it is now well established, that ocean processes were a key determinant of climatic change over recent geological history (i.e. the Quaternary glacial-interglacial cycles). More recently, the ocean has absorbed about 30% of anthropogenic carbon dioxide emitted since the start of the industrial era (Friedlingstein *et al.*, 2022), decreasing ocean pH by 0.1 units in the process (von Schuckmann *et al.*, 2020) Between 1955 and 2010, the ocean is estimated to have absorbed 90% of the excess heat resulting from the fraction of anthropogenic greenhouse gases which still remain in the atmosphere (carbon dioxide as the dominant contributor – up to 80%) resulting in surface ocean warming by >0.1°C per decade over the last 40 years globally (Merchant, Allan and Embury, 2025) and 0.3°C per decade around the UK (Cornes *et al.*, 2023). Without the dominance of heat uptake by the ocean, the lower atmosphere could have warmed by >30°C (Whitmarsh and Czaja, 2015). However, absorption of excess heat and carbon by the ocean, alongside a warmer climate that is resulting in, for example, a substantial amount of fresh water being added to the ocean from ice sheets, has far-reaching consequences on the physics, chemistry and biology of our ocean, as well as the feedbacks that are critical in regulating the ocean and climate system.

Warming is altering ocean circulation by perturbing density gradients, which together dictates how the ocean stores and transports mass, heat, carbon and nutrients, with consequences for multiple biogeochemical and biological processes including, for example, oxygen distributions, productivity and biodiversity. In the high latitude ocean, increasing temperatures are shrinking the cryosphere, via mass loss from ice sheets and glaciers, loss of sea ice and increased permafrost melt (Meredith *et al.*, 2022). Freshwater discharge from ice melt in the northern American (groundwater contribution to streamflow increase of 0.7– 0.9% yr^{-1} between 1949-2005; Walvoord and Striegl, 2007) and Eurasian Arctic (23% increase in minimum flow or 8% in mean flow when averaged across all months between 1936-1999; Smith *et al.*, 2007) has increased over the last century, contributing to a global increase in sea level. The Ice sheet Mass Balance Inter-comparison Exercise (IMBIE) Team reported a global mean sea level rise of 10.8 ± 0.9 mm due to accelerated ice loss from the Greenland Ice Sheet between 1992 and 2018 (Shepherd *et al.*, 2020). Added to this, increased temperatures result in the expansion of seawater, which contributes around 50% of the overall 20 cm sea level rise from 1901-2018 (IPCC, 2023). Ocean warming has already committed the West Antarctic Ice Sheet to significant melt over the coming century, regardless of future carbon mitigation scenarios (Naughten, Holland and De Rydt, 2023), whilst increased freshwater from ice melt and changes in regional winds have reduced the deep global overturning circulation by up to 30% in some regions (Gunn *et al.*, 2023; Zhou *et al.*, 2023). Freshwater input from the Greenland Ice Sheet is also influencing stability of the Atlantic Meridional Overturning Circulation (AMOC), prompting ongoing debate about the potential for a tipping point to be breached in the coming century (e.g., Rahmstorf, 2024).

Marine organisms are characterised by defined optimal thermal ranges. Ocean warming related changes in water temperatures may thus cause local temperatures to reach or exceed these limits, driving poleward migration – a phenomenon known as 'borealisation'. Such shifts have uncertain consequences for biodiversity and ecosystems, particularly in polar regions where more species are projected to lose habitat than gain it under future warming scenarios (Genner, Freer and Rutterford, 2017; Griffiths, Meijers and Bracegirdle, 2017). Alongside long-term warming, the increased frequency, duration and intensity of marine heatwaves is driving acute thermal stress, mass mortality events, and coral bleaching, with severe and often irreversible consequences for local ecosystems. While mobile species can shift their distribution in response to warming, stationary or habitat-specific species such as corals, seagrass and benthic invertebrates lack the ability to migrate, leaving them vulnerable to thermal extremes and habitat degradation. The loss of foundational species undermines ecosystem structure and function, disrupting food web stability and diminishing productivity – impacting, e.g., fisheries. This has direct implications for food security, particularly in regions where communities rely heavily on local marine resources, e.g., island nations. Furthermore, there are feedback mechanisms between marine organisms and ocean biogeochemistry – biological processing carried out by marine species impact dissolved constituents, including nutrients and climate active gases like carbon dioxide and nitrogen dioxide, through a variety of processes such as the production and respiration of organic matter.

In addition, **warming enhances ocean stratification** (the layering of water by temperature and density) **which reduces vertical mixing**. This limits the upward transport of nutrients from deeper waters to the surface, constraining primary productivity, and hinders the downward transport of oxygen and other gases by affecting gas diffusivity, exacerbating midwater oxygen loss and limiting ocean-atmosphere exchange rates. As a result, global dissolved oxygen has declined by more than 2% (4.8 ± 2.1 petamoles) since 1960, a process termed 'deoxygenation' (Schmidtko, Stramma and Visbeck, 2017). Concurrently, the ocean's uptake of anthropogenic carbon dioxide has reduced surface ocean pH by over 0.1 units from the pre-industrial average of 8.17, leading to ocean acidification (Jiang *et al.*, 2019). These chemical changes increase the vulnerability of mineral-producing plankton and coral reefs to dissolution, threatening up to a quarter of marine species and jeopardising the food security and livelihoods of millions of people globally (Hoegh-Guldberg *et al.*, 2007). Changes in carbon export may also contribute to deoxygenation.

The ocean also affects the climate through a range of atmospheric interactions and feedbacks. **A warmer ocean generates stronger and more frequent storms, with consequences for ocean safety and coastal communities** (Kendon *et al.*, 2025), and for hazard forecasting and management. Any increased frequency and/or severity of extreme events can also interact with rising sea levels to increase the likelihood and severity of coastal flooding and infrastructure damage (see Chapter 7).

Feedbacks between the biological, chemical, and physical components of the ocean and related Earth systems are critical to maintain a steady state of element cycling and biological and physical processes (e.g. the ocean carbon cycle; Katavouta and Williams, 2021). However, climate change is altering these feedback systems. The consequences of this over space and time are poorly understood. Past climate changes, often reconstructed using marine sediment archives, provide longer-term perspectives on the observed climate change signals in the modern ocean. These underscore the potential for large-scale responses in modes of global scale circulation patterns and consequently regional climates to oceanic warming and enhanced fresh meltwater input, the consequences of O_2 loss and CO_2 gain in warmer waters, and the relative rate of present-day warming compared to the natural variability of the past (e.g., Thornalley, Elderfield and McCave, 2009; Foster *et al.*, 2018; Thornalley *et al.*, 2018; Tierney *et al.*, 2020).

4.1.2. National and International Coordination

Major international efforts are being made to document and assess the impacts of climate change on the ocean (most substantively through the International Panel on Climate Change [IPCC]). The evidence collated is a key source of scientific information and guidance used by the United Nations Framework Convention on Climate Change and to establish agreements and policies for carbon emission and/or temperature targets as, for example, set within the Paris Agreement. The IPCC commissioned a Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC; Intergovernmental Panel On Climate Change (IPCC), 2019), which highlighted the impacts of climate change on all facets of the marine environments, from the tropics to the poles, and coast to the deep ocean (Figure 4.1). There is established international guidance on sustained observation requirements for monitoring climate change. The UN Global Climate Observing System (GCOS) sets requirements for observation of Essential Climate Variables (ECVs). The GCOS Implementation Plan is presented to UNFCCC and is an authoritative guide for observing climate. A subset of the Essential Ocean Variables (EOVs) are also ECVs (Global Climate Observing System, 2025). A GOOS supplement highlights the ocean actions. GCOS also provides authoritative guidance such as the Climate Monitoring Principles (Global Climate Observing System, 2024). Further international coordinated efforts are provided by the UNEP Regional Seas Conventions, which bring together neighbouring countries to collaboratively monitor, assess and protect shared marine environments under shared agreements. The Global Ocean Acidification Observing Network (GOA-ON) enables international collaboration in monitoring ocean acidification by outlining standardised methods, global data access, and capacity sharing to build our understanding of regional impacts of acidification on marine ecosystems. The Argo programme provides global coverage of ocean circulation and variability through an array of autonomous floats that profile the upper 2000 m of the ocean, measuring temperature, salinity and, increasingly, biogeochemical parameters. Such global scale initiatives are further complimented by regional studies. For example, RAPID and Overturning in the Subpolar North Atlantic Program (OSNAP) are transatlantic observational programmes that track changes in heat, salt, and mass transport to better understand the Atlantic Meridional Overturning Circulation (AMOC), a critical component of the global climate system. Collectively, these initiatives play a critical role in developing global ocean observing capabilities and informing evidence-based policy in response to climate change.

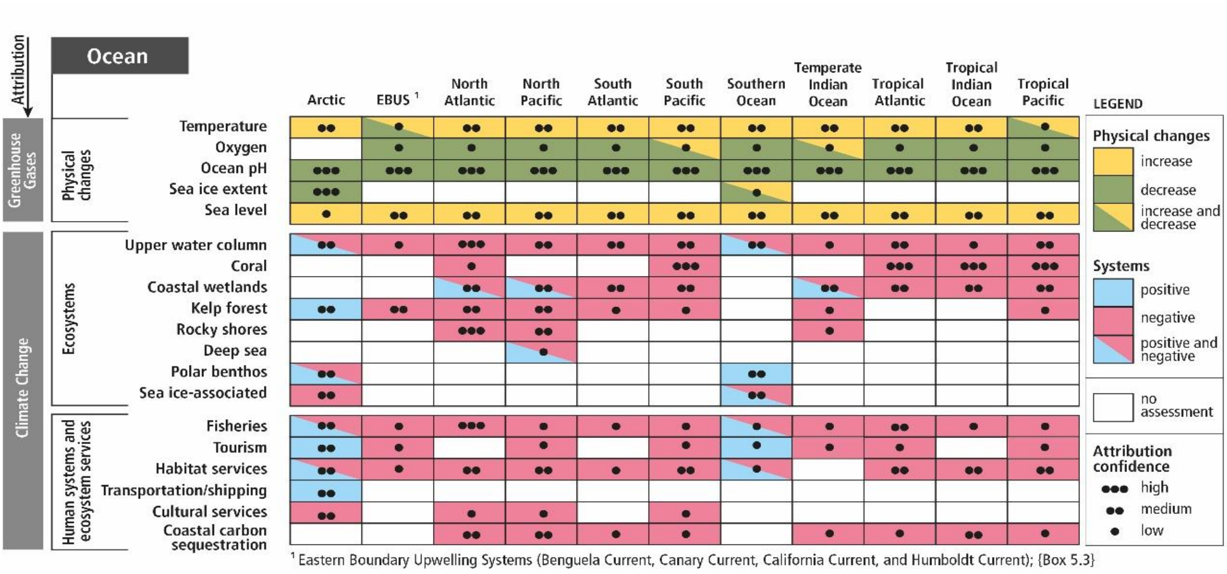

Figure 4.1: Synthesis of observed regional hazards and impacts in the ocean regions assessed in SROCC (IPCC, 2019).

The UK provides support to the World Climate Research Program (WCRP) by funding and carrying out research that aligns with WCRP objectives: '(1) to advance fundamental understanding of processes, variations and changes in the climate system; (2) to predict the near-term evolution of the climate system; (3) to refine the ability to anticipate future pathways of climate system change; and (4) to support the development of theory and practice in the integration between natural and social sciences'. These activities include collaboration through participation in committees and working groups; engaging in policy decision-making processes through the government to integrate the latest scientific findings into negotiations and agreements; and building research capacity through training initiatives and resource sharing throughout the WCRP network. UK climate research initiatives cover topics including, but not limited to, enhancing modelling, climate impacts, and ocean-atmosphere and ocean-cryosphere interactions. Notably, WCRP Lighthouse Activities (World Climate Research Programme, 2025) are in development to address critical objectives by rapidly advancing technologies and frameworks to mitigate climate change impacts to society through transdisciplinary collaborations across and outside the WCRP community. These activities focus on developing new insights into the Earth's climate system, improving predictions of its short-term variability and long-term trends, and leveraging new technologies to create a digital twin of the Earth for more accurate simulations.

In the UK context, the UK National Climate Science Partnership (Met Office, 2021) has developed a world-leading strategic partnership by combining capability in climate observing and prediction via investment in science and computing. UKNCSP works with public and private sectors to ensure decision-makers and businesses have access to climate information to build resilience and adaptation strategies. The UK Marine Climate Change Impacts Partnership (MCCIP; Marine Climate Change Impacts Partnership, 2021) is the primary independent source of evidence and advice for how climate change is affecting the UK marine and coastal environments. As well as providing evidence headlines through report cards and papers, MCCIP works with a range of stakeholders, including marine industries, to assess risk and build solutions to marine climate change impacts in the UK.

Past climatic and environmental changes are used in the IPCC reports to provide perspectives longer than observational records and as a way of understanding the mechanics of the Earth system under different boundary conditions. For example, estimates of past climate sensitivity were a key constraint in the most recent AR6 assessment (IPCC, 2023). Much of the data for, and modelling of, these past conditions is generated through international collaborative programmes, such as the International Ocean Discovery Program (IODP; International Ocean Drilling Programme Science Office, 2025), PAGES (Past Global Changes Project Office, 2025) and the International Continental Scientific Drilling Project (ICDP; (The International Continental Scientific Drilling Program, 2025).

4.2. Anticipated Scientific Developments by 2040

The following are identified as ongoing or potential emerging broad science priorities, which may be driven by societal needs, emerging applications, technological or methodological advances, alongside fundamental advances in understanding and model developments requiring improved process understanding.

Building our understanding of magnitudes of, and controls on, variability in the climate system. Current assessments, such as the IPCC-SROCC (2019), indicate that changes in multiple aspects of the climate system can be expected over the coming decades. However, uncertainties associated with specific changes vary greatly, including in relation to multiple system components relating to marine productivity, biodiversity, ecosystem services, resources and hazards (Figure 4.1). Consequently, there remains an ongoing requirement and challenge to both observe and monitor changes in these key system components. Alongside this, developing an enhanced understanding of the drivers and feedback associated with expected or potential changes is required, in order to ultimately reduce uncertainty and generate the enhanced predictability required to inform management and policy. Both monitoring and developing enhanced system understanding will likely require observations of multiple system characteristics at a wider range of space and time scales than is currently achievable or at least routinely undertaken.

Enhancing our understanding of weather systems and extreme events. In addition to intermediate (decadal to centennial) scale changes, multiple aspects of the climate system can also have substantial impacts on the natural system and human activities over shorter timescales. This includes individual storm events, marine heatwaves, flooding and other extreme climatic events. Enhanced early warning and predictability of such events will require the collection of increased volumes of near-real time data globally, including in difficult to access regions, while maintaining measurements calibrated to climate standards. Better sampling of a range of climate related physical characteristics will be needed in the transition zones between continental shelves and open ocean, which are essential for weather forecasts, as well as for studying the biogeochemistry and productivity of shelf seas. Improved model fidelity and increased predictive capacity will require better data inputs and improvements to climate models. As for the case of longer timescales, improved representation of fundamental processes in models requires enhanced mechanistic understanding of underlying processes as well as better representation of the feedback between processes.

Strengthening our understanding of the effects of the rapidly changing polar regions on the regional - global climate system. Through their influence on the large-scale atmospheric and oceanic circulations and sea level rise, polar regions play a major role in the climate system. These regions, including the Arctic and Southern Oceans, are experiencing some of the most rapid and significant climatic changes, with major implications for natural system behaviour, alongside potential socio-economic and geopolitical impacts. Better sampling of heat content, carbon and freshwater fluxes in polar/subpolar regions, particularly the Southern Ocean, are needed to further develop our understanding of ocean circulation change and heat and carbon uptake from the atmosphere and improve climate forecasting. This requires improvements in observations of ice-covered regions and observations during winter, and improvements in model representation of ocean processes. Better understanding of ice-ocean interactions will require novel under ice and ice-shelves measurements which will inform ice-sheet model development and predictions of sea level rise. The models in turn need improved process representation of ice dynamics and ice-ocean interaction, particularly in ice shelf cavities, and to be fully coupled with Earth System Climate models.

Building our understanding of the effects of climate change on ecosystem function and ocean productivity. Enhancing our understanding of how ecosystems may be impacted as the ocean warms further and circulation patterns continue to shift, has implications for protecting ocean health and food security. Improved forecasting of ocean productivity and prediction of marine ecosystem changes will again require both enhanced monitoring and observational capabilities of multiple physical, biological and chemical system characteristics as well as enhanced process understanding. Establishing the effects of simultaneous ocean warming, stratification changes, the presence of marine pollution, ocean acidification, and oxygen depletion will require observations of multiple ecosystem drivers (e.g., ocean warming, marine pollution and deoxygenation) alongside conceptual, theoretical and digital tools to understand how these drivers interact.

Developing our understanding of the risks and effectiveness of CO_2 removal (CDR). CDR is rapidly becoming a global scientific priority. By 2040, an increasing number of trials of a range of marine-based CDR (mCDR) projects might be expected. A key scientific priority will be to assess the risks and effectiveness of proposed mCDR efforts, such as alkalinity enhancement and stimulation of the biological carbon pump, as well as potential impacts on the marine system of CDR or alternative geo-engineering approaches applied to other aspects of the Earth system, such as the cryosphere or atmosphere associated albedo manipulation. Technology and theory able to measure the direct and indirect impacts across a range of potential CDR methods and at local to global scales, alongside quantification of benefits and assessment of risks and feedbacks will be critical in making decisions about their large-scale implementation or abandoning mCDR. A growing portfolio of projects around the world are already investigating the efficacy of and impacts of mCDR (e.g., Ebb Carbon, Seafields, Project Vesta) and will likely produce results within the window to 2040. Thus, it will be important to further consider environmental monitoring frameworks and practices and verification approaches that will be required to oversee any implementation of CDR technologies and particularly the differentiation of any impacts from other natural and anthropogenic system changes.

Enhancing our interpretation and Quality Control of large, new data streams. All of the above broad fields, alongside a wide range of fundamental research into the broad climate system, will continue to leverage off and direct advancements in a range of technologies. Advances in autonomy and sensor technology are already creating vast new datasets. For example, the global Argo array, has been transformative in our ability to observe the ocean at global scale over multiple timescales. Machine learning is increasingly being used to interpret these and other datasets and extend the information that can be extracted from them. However, careful quality control and interpretation will be needed to use these new types of data. Some examples of future pathways and advantages in this field include training ML algorithms to process automated quality control of observational data (to identify e.g. outliers, sensor malfunctions), pattern recognition and anomaly detection (to detect extreme events, e.g. marine heatwaves and harmful algal blooms), and faster integration of diverse data streams (e.g., physical, biological, chemical for holistic ecosystem overview).

4.3. Key Science Questions, Knowledge Gaps and Uncertainties

Building on the anticipated broad fields of scientific developments outlined above, the following more specific scientific questions and associated uncertainties and knowledge gaps can be identified.

Will the ocean continue to take up a significant amount of anthropogenic heat?

The ocean is estimated to have absorbed the majority (~90%) of anthropogenic heat generated over the past century. Providing good future estimates for this fraction, as well as monitoring ongoing change are crucial for predicting the future ocean climate. We require better understanding of the processes of heat uptake, for example, what role the ocean plays in setting the mean state and variability of ocean sea surface temperature and other upper ocean properties such as mixed layer depths. We also need to understand and ultimately predict how heat uptake and other upper ocean processes are impacted by changing ocean dynamics and boundary forcing, i.e., from a warming atmosphere and melting cryosphere, alongside how these changes impact climate sensitivity, e.g., through cloud feedbacks and the pattern effect. Overall, a number of specific questions remain, including the fundamental dynamics that set ocean heat uptake efficiency, the consequences of polar amplification and whether global climate sensitivity is very different in a world with warmer poles and reduced ice sheets. Addressing these questions will require the ability to observe the associated components (e.g. global surface and whole ocean heat content) of the contemporary marine system, alongside using marine based infrastructure to enable collection of material to enable paleo-reconstruction of past changes and hence better constraints on future predictions.

Will the ocean continue to take up a significant amount of anthropogenic carbon?

The ocean holds the largest reservoir of carbon which is exchangeable between Earth system components on decadal to century timescales and hence regulates climate via its control on atmospheric CO_2. At present, the ocean takes up around 25% of anthropogenic CO_2 emissions through the so-called solubility pump (i.e. physical-chemical processes), mitigating against additional levels of climate change, while also driving ocean acidification (Meredith *et al.*, 2022). Whether or not this ocean sink will continue at the same level is a critical component of policy efforts to align emissions strategies to the remaining carbon budget available to stay within specific warming thresholds (e.g., 1.5°C, 2°C), especially on regional scales (Friedlingstein *et al.*, 2025). While we understand the fundamentals of how both the solubility pump and biological pump operate to determine the overall ocean carbon sink, we have lower confidence in understanding how simultaneous modifications to the ocean environment generate different types of feedback mechanisms, through physical, chemical and biological processes, that may affect long-term predictability of oceanic carbon uptake and storage (Intergovernmental Panel On Climate Change, 2019). This is particularly important in the Southern Ocean, which dominates the ocean-atmosphere carbon exchange, but is presently poorly observed, particularly in some sectors, and where significant observation-model mismatches exist for flux estimates from seasonal to decadal timescales (e.g. Bushinsky *et al.*, 2019; Meijers *et al.*, 2023). Significant ongoing shifts in regional winds, stratification and biological activity due to rapid sea ice and ice sheet change, means that resolving this discrepancy is critical for longer term climate prediction.

Improved estimates of global ocean carbon uptake by the solubility pump, particularly in under-sampled regions and seasons (such as the Southern and Arctic oceans and particularly deep-water formation zones), are thus needed to better constrain and partition the present-day global carbon budget, while the ability to continue making the observations required to make such measurements will be crucial in establishing whether the sink is changing. The present gaps between Southern Ocean carbon uptake in model, ship-based and autonomous instrument assessments, urgently need to be rectified, through improved wintertime and under ice measurements, with commensurate efforts to improve carbon process representation in models, particularly Earth System Models. Moreover, improved quantification and mechanistic understanding of the Biological Carbon Pump (BCP) and its interactions with CO_2 solubility and ocean circulation, at both local and global scale, are needed to improve models of future ocean carbon uptake and deoxygenation and to assess the efficacy and risks of mCDR efforts.

Direct estimates of both heat and carbon uptake require sustained observations of air-sea fluxes, while parallel research into upper ocean dynamics can further increase understanding of ongoing changes and reduce uncertainties. Currently, large uncertainties and the lack of measurements in remote locations (again including the Southern Ocean, alongside many remote areas of the larger oceanic basins) and some seasons (e.g. through seasonal sea ice) prevent us from accurately capturing global and regional changes in air-sea fluxes. Surface microlayer processes are particularly important in this context; however, they are difficult to sample reliably, and available observations often represent only brief snapshots in time. As a result, these processes are poorly understood and hence frequently omitted from models. Inaccurate data on ocean-atmosphere interactions then lead to biases in global heat and carbon budgets, as well as inaccurate global climate models. Uncertainties also remain in the drivers and future evolution of the mixed layer depth and stratification under a changing climate, with implications for the potential expansion of low productivity sub-tropical gyre systems as well as reduced ventilation of the eastern boundary systems where the major oceanic Oxygen Minimum Zones (OMZs) are located (Gruber, 2011). Together with reduced oxygen solubility due to warming and potentially changes in the biological pump, the future evolution of stratification and mixed layer depths may thus influence key biogeochemical processes acting in OMZs (such as fixed nitrogen and N_2O production and thus further affect the sequestration of anthropogenic heat and carbon.

How can we detect and attribute climate change impacts on the ocean beyond natural variability?

Detecting whether changes in ocean properties can be attributed to human activity or to natural variability is a critical part of managing and predicting impacts across an array of systems. Identifying the causal link between external drivers and key ocean properties requires an assessment of the signal to noise ratio in a statistically confident way. It underpins the assessments made by the IPCC and others about how human activity is modifying our natural system (Meredith *et al.*, 2022). At present, we conduct detection and attribution exercises in the ocean on properties including sea surface temperature, ocean acidification (pH and the broader carbonate system), oxygen concentrations and productivity (e.g., Bindoff *et al.*, 2019). These assessments require high quality observations of sufficient spatiotemporal density but also depend on the level of natural variability and mechanistic understanding of the property in question. While we have the highest levels of confidence for detecting human driven changes in ocean heat content, salinity and acidification (albeit recognising that these changes are currently predominantly occurring in the upper ocean, but would be expected to penetrate deeper over circulation timescales), we require improved observational records for other aspects of the climate system, such as the AMOC, and lack sufficient constraints on the overlapping physical and biogeochemical drivers for oxygen and productivity (Meredith *et al.*, 2022). Similarly, recent shifts in the sea ice and dense water formation around Antarctica can be extremely dramatic but short records and poor process understanding make it hard to attribute these changes to drivers.

How can we better constrain tipping points and abrupt changes over multiple timescales?

Interactions between components of the ocean and the associated wider Earth system are often characteristically non-linear. Such non-linearities are highly important, as feedbacks can lead to unanticipated cascading impacts and accelerating change. These feedbacks have been recognised by the IPCC as key areas of uncertainty undermining accurate forecasting of risk. A key characteristic of non-linear systems is the potential for so-called tipping points. Climate-related tipping points may occur as the result of small continuous, or abrupt, perturbations that can push system components beyond a critical threshold, leading to a new (semi-)stable state. This new state may, in turn, trigger other recognised potential tipping points, leading to multiple changes in Earth systems which could have catastrophic consequences for the Earth's climate, ecosystems, and human societies. For example, the disintegration of the Greenland and Antarctic ice sheets will lead to major sea-level rise, displacing over a billion people living in coastal regions. The limited understanding of the mechanisms driving tipping points, coupled with uncertainties about their interactions, hinders accurate predictions of the consequences of global warming and effective mitigation planning. Determining the timescales at which tipping points might occur (decades to millennia) and their likelihood, remain active areas of research. Over recent decades, the estimated global temperature threshold for triggering tipping points of potential tipping elements in IPCC reports has been revised downward, from 5°C to 1°C (which we have now surpassed; Lenton *et al*., 2019), whilst some changes, such as the melting of parts of the West Antarctic Ice sheet, are already irreversible on centennial timescales (Naughten, Holland and De Rydt, 2023).

As an example, the future evolution of the AMOC has been identified as a key tipping element in the Earth system (Ditlevsen and Ditlevsen, 2023). The AMOC affects the Earth's climate by redistributing tropical ocean heat to higher latitudes and by regulating the transport of carbon dioxide and oxygen. A changing AMOC has repercussions on UK weather, extreme events, storm intensity, sea level rise, and fisheries – to name a few. A major weakening or collapse of the AMOC could drastically alter the climate and agricultural systems of the northern hemisphere. Due to a lack of agreement between modelled and observed AMOC characteristics and changes, which results from a poor understanding of the processes driving AMOC changes (e.g., freshwater input), there is low confidence in the magnitude of the predicted AMOC decline and whether it will be abrupt or gradual. Many questions remain, including what are the relative impacts on AMOC of increased freshwater input and warming? Are there different modes of AMOC behaviour and how might these impact circum-North Atlantic climate? What impact will an altered AMOC have on pelagic ecosystems, deep-ocean oxygenation and ocean carbon storage? What research is needed to answer these questions and thus, what infrastructure is needed?

Geo-engineering: how do we use the ocean to support the pathway to net zero safely?

Carbon dioxide removal (CDR) is becoming more widely recognised as a potential critical component towards achieving internationally agreed climate targets (Intergovernmental Panel On Climate Change, 2021). A range of marine (m)CDR approaches have been proposed that either increase the capacity of seawater to absorb atmospheric CO_2 (via manipulation of seawater chemistry, including ocean alkalinity enhancement and electrochemical carbon removal) or enhancement of biological processes (i.e. the rate of macroalgae and microalgae production of organic carbon and subsequent sequestration and/or subseafloor burial of some fraction of this material) (e.g., A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration, 2022). Although some small-scale field trials are now underway, large gaps remain in our understanding of both the risks and effectiveness of the proposed interventions (Ocean Visions, 2025). An urgent scientific priority over the coming decades will be to improve our capability to monitor and understand both the positive and negative impacts of mCDR efforts, including the potential for ineffective CO_2 sequestration, the direct impacts of large-scale mCDR operations and potential feedbacks/impacts on other system components. Integrated observational technologies and modelling approaches will be required that enable ocean carbon uptake and any associated effects to be tracked across both local and regional scales and over multiple timescales. Moreover, proposed CDR techniques deployed in other components of the Earth system can also influence the marine environment. Indeed, CDR applied in any one component of the Earth carbon cycle must ultimately influence the other components, as fluxes between the rapidly exchangeable pools adjust in compensation to the imposed perturbation (Keller *et al.*, 2018; Oschlies *et al.*, 2023). Moreover, other geo-engineering approaches addressing the planetary energy budget directly through adjustments to albedo, such as sea ice thickening or stratospheric aerosol injection, would all likely have resulting direct or indirect feedback on marine systems. Consequently, a future marine observing infrastructure may need to be developed with consideration for, and in collaboration with, broader observing systems for other system components.

How did the ocean modulate climate through Earth history?

As the ocean stores around 1000 times more heat and 50 times more carbon than the atmosphere, small imbalances in oceanic carbon cycling and heat storage have had dramatic impacts on atmospheric carbon concentrations and climate on geological timescales. This is well-illustrated in the chain of events that started around 19,000 years ago and led to the last deglaciation – Earth's most recent climate tipping point. Twenty thousand years ago, Earth was in the depths of an ice age with km-thick ice sheets covering much of Northern Europe and North America. Regular changes in Earth's orbit began to melt these ice sheets around 19,000 years ago, with the freshwater released to the North Atlantic slowing down the AMOC leaving more heat stored in the Southern Hemisphere. This in turn led to the melting of sea ice in the Southern Ocean, releasing the lid that had kept CO_2 in the deep ocean and away from the atmosphere for thousands of years. In the following 10,000 years, CO_2 concentrations rose by around 60%, the great ice sheets melted and global climate warmed by 5°C causing the Earth to enter its current interglacial climate state. Although this most recent transition tipped the Earth into a state suitable for the development of much of modern civilisation, it was simply the latest of 50 such transitions experienced by the Earth as orbital variability caused oscillations between glacial and interglacial climate states over the last 2.6 million years.

In addition to being a major driver of climate change on geological timescales, the sediments that accumulate on the seafloor are a vital archive of information on ocean circulation and climate of the past. Calcium carbonate shells of foraminifera can record concentrations and/or isotopic compositions that can be related to aspects of the water they grew in and the wider environment, enabling estimates of, for example, water temperatures, ice-volume, ocean pH and atmospheric CO_2. These can be further related to other marine sediment records such as dustiness of the atmosphere to derive system interactions. Such archives thus provide crucial knowledge and rigorous tests of our understanding of and ability to predict climate interactions. Further development and ground-truthing of our understanding of the ocean's role in modulating global climate thus requires the ability to sample and analyse palaeoceanographic records (sediment cores, corals, microfossils, geochemical tracers), alongside the ocean drilling infrastructure and seafloor observatories to monitor sedimentary processes that impact paleoclimate signals. This work will need to be supplemented by advances in analytical and dating methods, non-destructive and *in-situ* technologies, global ocean observing systems (with open data access), and integrated palaeoceanographic data streams to inform more accurate Earth system models.

How will sea-levels change over the coming decade?

Accelerating sea-level rise (SLR) and an increased likelihood of extreme weather events will heighten the adaptation needs of coastal communities. Global mean sea-level rise primarily results from the thermal expansion of seawater and the melting of glaciers and ice sheets. Anthropogenic subsidence further exacerbates regional sea-level rise, particularly in delta regions. Significant uncertainties regarding processes driving ice sheet instabilities, particularly in the Antarctic ice sheet where tipping points are likely to exist in some regions, lead to substantial variability in SLR projections beyond 2050 (Oppenheimer *et al*., 2019) and uncertainty ranges beyond 10 m on centennial timescales (IPCC, 2023). Furthermore, extreme events like storms, marine heatwaves, and tidal surges are projected to become more intense and frequent in a warming climate. Observational data – from tide gauges to satellite measurements – are essential for understanding the impacts of extreme events on SLR but remain insufficient in many regions globally. Improved process understanding and observational monitoring of the polar ice sheets, and particularly ocean-ice shelf interaction, is central to the successful modelling of future SLR. Mitigating the impacts of SLR will require a combination of strategies, including protection (e.g., seawall or barrier construction), accommodation (e.g., adapting coastal infrastructure and land use practices), advancement (e.g., land reclamation), retreat and relocation, and ecosystem-based adaptation (e.g., reef/seagrass/mangrove restoration). Combining these in an integrated approach will offer benefits for the marine environment and humans and is essential to ensure adaptive capacity and security for coastal communities.

Will the marine food supply be sustainable for humans in a changing climate?

In addition to its role in ocean carbon storage, biological productivity is the foundation of ocean ecosystems and fisheries. Primary productivity is projected to decrease as the ocean warms, due to suppressed nutrient transport to the surface through increased low latitude stratification, but the magnitude of decrease is highly uncertain (Figure 4.1). Over the next decades, it will be critical to measure whether such a decrease does occur and understand the potential drivers, including changes in macro and micronutrient supplies, stratification, nitrogen fixation, light, dissolved O_2, changes in metabolism, alongside associated shifts in plankton community structure and biodiversity in a warmer ocean. Understanding how these shifts feedback to broader climate and biogeochemical cycles remains incomplete.

The marine environment is a source of protein for over 3 billion people worldwide (FAO, 2024). It is critical that the harvesting of marine resources, including fish, shellfish and other invertebrates, is sustainable to support human populations and health. Fish populations are ultimately sustained through primary productivity driven by the phytoplankton at the base of the food chain, alongside removal by predators. The projected global decline in marine net primary production thus threatens to reduce fish biomass, with implications for society. However, we have a low level of confidence and high uncertainty in projections of net primary production (NPP) which will stunt our ability to manage fisheries. Much of this uncertainty can be related to corresponding uncertainties in the climate related drivers of the system, in particular, the details of changes in physical forcing. Critical knowledge gaps related to the resilience or adaptation of fisheries to multiple concurrent stressors such as warming, ocean deoxygenation and habitat loss exist, which may drive populations towards new regions, with consequences for local ecosystems and net geographic migration.

4.4. Observation and Product Requirements

Effectively addressing the scientific themes and questions outlined above will require integrated, multi-faceted marine observational infrastructure which can capture the required data and information, with accuracy and precision, at time and space scales appropriate to the processes under study (e.g. Stommel 1963). Volume of data must also be sufficient to address the questions raised. In many cases, data requirements will need to be tailored to the scientific context / question being addressed and as such are more likely to be collected in a specifically designed 'experimental' study. At present, such studies would typically be supported by more versatile infrastructure platforms, such as ships and more bespoke autonomous systems. Other questions, in particular those requiring long timescale and/or large spatial scale observations, may often be addressed using more general sustained observations, which may typically consist of a more limited set of observable variables. Such observations may also be provided by ship-based platforms (e.g. using so called repeat hydrography sections or mooring arrays deployed from vessels), ships of opportunity sampling and increasingly augmented by more mature autonomous observing systems such as the international Argo programme or use of fleets of various types of autonomous vehicles (e.g. buoyancy driven and wave gliders, long-range/duration AUVs submarine vehicles).

4.4.1. Variables

A generic list of parameters is provided by the internationally recognised EOVs (see Table 4.1), providing a starting point for some of the readily observable physical, (biogeo-)chemical and biological aspects of the marine system which most directly interact with and/or are impacted by the climate system on relatively short (i.e. decadal-century) timescales. Such variables often provide the basis, in particular, for sustained or large spatial scale observations, but do not provide an exhaustive list of all aspects of the system which are currently observable, using the most advanced or technically / logistically challenging methods. Indeed, an extended list can be envisaged which would provide some of the further information necessary to address some of the questions above.

Table 4.1 Current list of Essential Ocean Variables and pilot variables for reference. Potential additions are listed in Section 4.7 (Table 4.2). * = in pilot phase. N.B.: Although listed, many are far from being achieved, particularly at depth and in high latitudes.

Physics	**Biochemistry**	**Biology and Ecosystems**
Sea state Ocean surface stress Sea ice Sea surface height Sea surface temperature Subsurface temperature Surface currents Subsurface currents Sea surface salinity Subsurface salinity Ocean surface heat flux Ocean bottom pressure Turbulent diapycnal fluxes*	Oxygen Nutrients Inorganic carbon (pH) Transient tracers Particulate matter Nitrous oxide Stable carbon isotopes Dissolved organic carbon Stable oxygen isotopes	Phytoplankton biomass and diversity Zooplankton biomass and diversity Fish abundance and distribution Marine turtles, birds, mammals abundance and distribution Hard coral cover and composition Seagrass cover and composition Macroalgal canopy cover and composition Mangrove cover and composition Microbe biomass and diversity* Invertebrate abundance and distribution*

For example, in addition to the internationally recognised ocean EOVs (Table 4.1), several other key state and rate measurements would be extremely valuable for addressing some of the above science questions, particularly in relation to the biogeochemical aspects of the system (Section 4.7, Table 4.2). Additional **state variables** include trace metal concentrations and bioavailability (productivity drivers), particle size (key to ecosystems and biological carbon pump), inherent optical properties (controls light penetration and global-scale proxies for biomass, community, and productivity), and ocean bottom pressure (OBP). Molecular techniques (frequently collectively termed ‘omics’) will continue to be increasingly applied in observing the biological components of the system, providing information on both community structure/biodiversity and physiology. Key **rate variables** include biological uptake/production of key elements and organic and inorganic compounds listed in EOVs (e.g. O_2, organic carbon, calcification, nitrogen fixation, biogenic silica production), remineralisation (of carbon and other elements and compounds), ingestion/grazing, egestion/faecal pellet production, biological growth, and physical fluxes of key EOVs, including active fluxes, sinking fluxes, and mixing and advective fluxes. Key **experimentally observable variables** relating to biological aspects of the system include maximum rates (growth, feeding, etc.), minimum rates (e.g. baseline respiration), and dependence of rates on key EOVs (e.g., T, O_2, nutrients, light, particle concentration). Additionally, as with many aspects of observational science, over decadal timescales there will undoubtedly be advances which will enable currently unobservable aspects of the system to be measured. As such, any future infrastructure will need to be flexible enough to incorporate advances in technology and indeed to facilitate the development of such advances.

Paleo-oceanographic proxies are critical for our understanding of how the climate system can vary and provide critical constraints to our models (both conceptual and numerical). Such proxies effectively allow estimation of key EOVs and other observable system characteristics from the past and their connection with past climate. Reconstruction of past state and rate variables beyond the observational record requires the application of proxies – surrogate measurements for the variable of interest. Development and measurement of these proxies frequently requires return of physical samples (sediments, cores) for analysis in state-of-the-art shore-based geochemical facilities (e.g. the NERC geochemical and isotope facilities, Diamond Light Source). Developing and applying proxies from marine sediments also typically requires empirical calibrations, in addition to experimental data. The former are reliant on the simultaneous measurement of corresponding present-day state and rate variables (e.g. Table 4.1), alongside sample collection of seawater, particulates, seafloor and subseafloor sediments.

4.4.2. Space/time Scales

As indicated above, there is an over-arching need for flexibility in spatiotemporal scales of observations. The overall infrastructure must allow for measurement and sampling of the ocean, seafloor and interacting components of the Earth system (atmosphere, cryosphere, lithosphere) at scales ranging from microscopic to global, sub-second to multi-decadal to enable the full range of potential questions and associated phenomena outlined above to be addressed and researched (Figure 4.2). Consequently, observation and experimental capabilities are often tailored to the specific time and space scales under consideration.

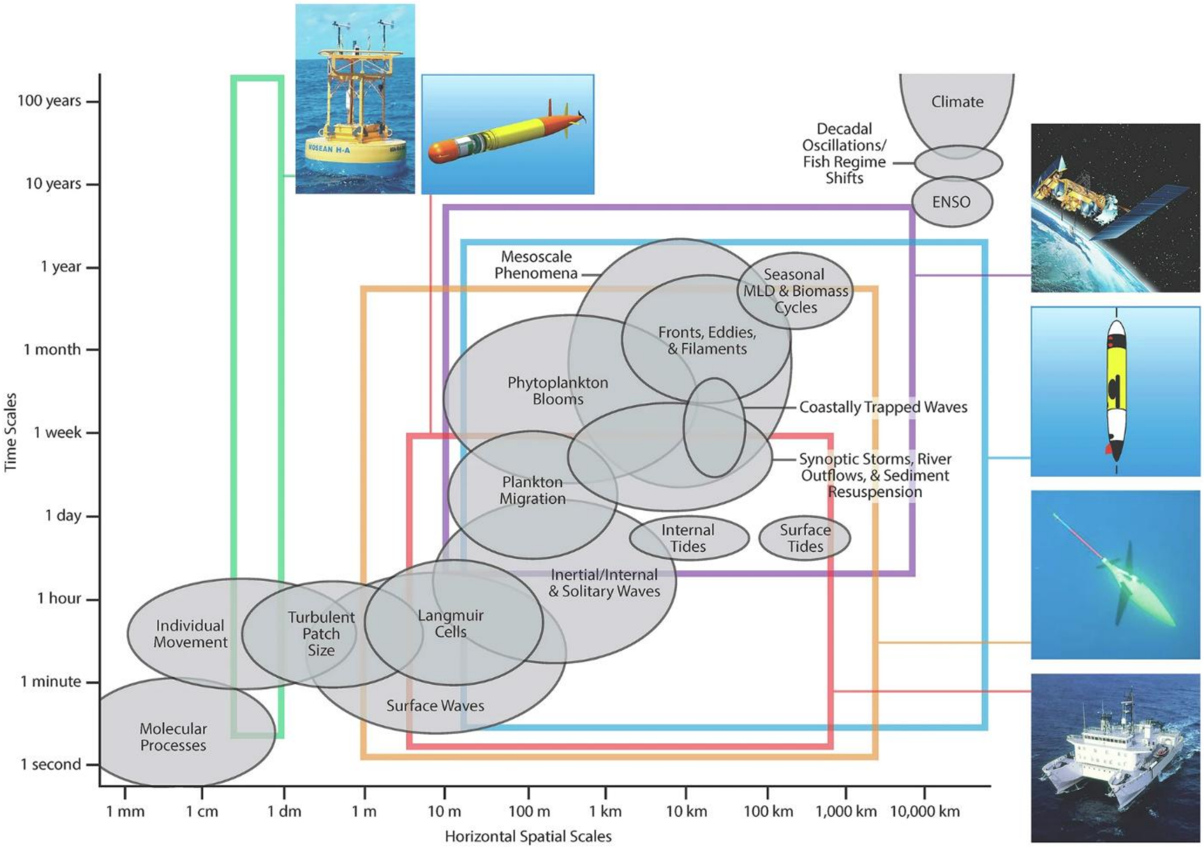

Figure 4.2. A 'Stommel diagram' of cross-scale time and space continuum for various ocean processes and phenomena and the corresponding approximate observational footprint for current observing platforms. platforms and ocean phenomena. Figure is from Garcia *et al.* (2025; following Stommel, 1963; Dickey, 1991; Karl and Church, 2017).

Beyond the directly observable scales, reconstructions of past ocean states and processes require proxies that can be applied over timescales of centuries to millions of years and coring of sediments and drilling of sedimentary rocks in key localities, in a range of water depths and to sub-seafloor depths of cm to km. Identification of coring sites needs characterisation of the seafloor and subsurface using marine geophysics. Given the scale of infrastructure required for such observations, there is inevitably some trade-off between the spatial extent and resolution of such material collection and associated measurements. An ability to address this scale issue would be highly scientifically valuable but presents considerable challenges with current technologies.

For sustained observations in support of climate science (for example in the calculation of ocean heat and CO_2 uptake, or variability of the AMOC), year-round multi-decadal timeseries are often critical. Global, continuous coverage of as many climate-linked variables as possible is a key priority, although observed variables and scales will undoubtedly need to be prioritised. For example, areas of particular challenge and importance present in regions with sea-ice cover or under ice-shelves and during harsh winter conditions where shipboard observations can be challenging. The mesopelagic and bathypelagic zones, the air-sea interface, the seafloor sediment-water interface, and pelagic/shelf/coastal transition regions represent further challenging environments to observe. This would be well supported by the early integration of routine satellite observations with observational efforts of these areas to ground truth. Examples of global scale observational and synthesis programmes exist (e.g. WOCE, Go-Ship, SOCAT, Argo, Geotraces), all of which required substantial international collaboration.

For targeted, experimental observations, the capability for measuring a range of physical and temporal scales from mesoscale to microscale is essential. When considering model development, the scales on which data are required to be collected are often informed by model resolution; it may not be necessary to capture all variables at the finest resolution, whereas mechanistic understanding and description of processes might call for as fine a detail as possible. Differing resolutions in time and space can still maintain the model output 'on track'. Variables have different inherent scales, for example, sea level data is collected hourly or longer, at 10s of kilometres resolution in shallow seas versus 100s of kilometres resolution in deeper waters, whereas waves and currents around small-scale coastal features may require measurements every second or metre, while direct observations of ocean mixing and turbulence may require observing systems capable of resolving cm to mm scales. Consideration of time and space scales is thus crucial to consider when designing and planning for observational infrastructure (see Section 4.5).

4.4.3. Accuracy and Precision

Accuracy requirements for any given variable are highly dependent on the science question they are used for. Detection of climate-driven changes requires accuracy better than the magnitude of the long-term trend, or in the worst case, a bias that is consistent over time. Such requirements can impose considerable technical challenges. As an example, observations of the carbonate system (stated under 'inorganic carbon' in Table 4.1) have to be of very high precision and accuracy when estimating oceanic uptake of anthropogenic carbon due to the perturbation being a relatively small change against a large background, but a lower accuracy and/or precision may provide acceptable measurements of the inorganic carbon system in the context of an experimental process study of a process which causes strong variability in the system over smaller time and space scales. Accuracy and precision must thus be considered alongside spatiotemporal observational scale in the design of a specific observing/experimental requirement, again necessitating the need for flexibility in platform, sensing and sample collection capabilities.

4.4.4. Products

Enhancing data availability and interoperability A large amount of marine data and marine infrastructure-based observations with relevance to climate system are already collected. Specific international programmes (e.g. Go-Ship, Argo, Geotraces) typically put in place systems and processes which allow for data to be findable, accessible, inter-comparable/operable and reusable (FAIR), but such systems are not currently generic. Efforts at collating and quality controlling large data sets collected across programmes and national systems and requirements have had some success (e.g. Glodap) but have usually required considerable resource. Products which leverage advanced digital tools to address this challenge would be highly valuable, including through the adding of value to already available data holdings.

The **ability to take and store water samples** would significantly open the ranges of variables that are potentially observable **using autonomous vehicles/platforms**. The use of autonomy will further expand the spatial coverage and temporal resolution of sustained observations, including most notably below 2000 m depth (including the sediment-water interface and the subsurface) and under ice. This will be a crucial step if ocean heat storage is to be evaluated – it is easier to measure global heat content change at the top of the atmosphere than from the deep layers of the ocean. Autonomous observations from gliders or similar pilotable vehicles that can extend to the ocean bottom (or at least 4000 m) should eventually significantly reduce the need to dedicate ship time to 'repeat hydrography' sections. This will improve the carbon efficiency of ships by allowing them to concentrate on process studies or more difficult to automate observations that require collection of samples.

Furthermore, there will be increased requirement for the intense measurement of multiple variables in one location over a sustained period of time – point ocean observatories that have a fixed set of high-resolution instruments covering every possible variable, that can also take additional specialist instruments for process studies for shorter periods of time. The UK currently has few fixed offshore observatories (e.g. Western Channel Observatory and Porcupine Abyssal Plain) that are instrumented in such a sophisticated way.

4.5. General Description of Key Capabilities

4.5.1. People, Skills and Partnerships

Ongoing developments in science requirements, alongside any changes in future marine research infrastructure, will all require continued education and adoption of new knowledge and skills within the UK marine science community. The challenges represented by climate change impacts on the ocean and reciprocal feedbacks on marine biota and biogeochemistry, as well as interactions with human activities across the ocean and wider planetary system, are inherently both multi/inter- (Dickey and Bidigare, 2005) and increasingly trans-disciplinary in nature (Renaud *et al.*, 2024). All areas of observational science will continue to be influenced by the ongoing expansion in the volume and diversity of data which can be produced by both existing and future sensors and platforms, as well as the advances in the digital tools used to analyse and interpret this data (see below). Researchers and students will hence need to continue assimilating the knowledge required to use new tools (Satterthwaite and Robbins, 2024) and enable interpretation of a complex interacting system (Renaud et al. 2024), while also being able to navigate the value chain from data through information to understanding and impact (Visbeck 2019). Collaborative networks will thus likely have to expand outside of traditional subject areas, for example engaging data scientists and social scientists alongside natural scientists and engineers.

The above will inevitably require close collaboration with the UK and international HE sector, alongside a broad set of stakeholders involved in R&D outside of the academic research community. Any accelerated pace of change generated by a move towards more rapid development and/or adoption of new technologies including sensors, platforms and digital will only make this requirement more acute.

Addressing the breadth and range of the space and timescales which will need to be considered in tackling many of the science challenges outlined above (Figure 4.2), will further require strengthening of the international co-ordination and collaboration across all these partnerships, building on examples of successful global scale observational and synthesis programmes (e.g. WOCE, Go-Ship, SOCAT, Argo, Geotraces). Moreover, to date these international programmes have often focused on e.g. physical (WOCE) or chemical (SOCAT, Geotraces) aspects of the system, whereas current and planned future co-ordinated and collaborative programmes (e.g. Bio-Go-Ship, Bio-Argo, BioGeoScapes) are increasingly bringing in biological observations, including omics and bio-optics, in combination with physical and chemical observations, to enable a more multi/interdisciplinary perspective. Such major international programmes and the infrastructure required to support them, will again require the development new skills and networks at individual to community scales.

4.5.2. Observational Infrastructure

Any overall observational infrastructure capable of measuring both the range of observable system characteristics (both individual parameters or variables, Table 4.1, or more complex system properties) and making observations over the range of required scales will necessarily need to be multi-faceted and flexible. Indeed, it has long been well recognised (Stommel 1963; Dickey 1991) that oceanic phenomena (both directly and indirectly climate related) have inherent time and space characteristics and are thus more amenable to observation with infrastructures which have observing footprints which overlap these (Figure 4.2).

For sustained global, continuous coverage of climate-linked variables, the international constellation of earth-observing satellites, the Argo float network, and the global drifter programme remain critical infrastructure which augment the measurements made by the global fleet of research ships. Satellites provide a wealth of physical parameters at the ocean surface, as well as optical properties that are used to derive an array of biological parameters with varying levels of accuracy. The Argo network is currently expanding coverage to deeper ocean depths (down to 6000 m) and under sea ice, and is expanding scope to cover six biogeochemical EOVs, again with varying levels of accuracy. Both satellites and Argo provide a previously unprecedented global coverage. Recent extensions will address key observation gaps, with new measurements of physical and biological variables and characteristics, including for example salinity, surface ocean currents and phytoplankton community structure becoming possible from space alongside increasing sensor capabilities on floats. Continuation of existing measurements will also increase our capacity to distinguish global climate change from other variability. However, these networks' ability to address climate science requirements also depends on sustained, widespread, high-accuracy calibration and validation measurements, often possible only with ship-based sampling. For climate variables not currently measured by global-scale networks, local sustained timeseries provided by moorings, satellites and/or repeat ship visits provide critical sustained coverage.

The ability to make targeted, accurate measurements of a wide array of key climate variables (Table 4.1) is crucial for both sustained observations and monitoring, as well as more experimental studies. However, the capability and capacity to design and implement complex, often interdisciplinary, experimental studies, which can require the simultaneous or sequential use of multiple different platforms (Figure 4.2) and enable the simultaneous measurement of many of these variables, is also a key requirement for maximising the potential of the UK oceanographic community to improve mechanistic understanding of the climate system (examples of different types of study addressing a range of key physical, biogeochemical and geological climate related research questions include DIMES, BLT-Recipes, Bio-Carbon, ROSES, SSB, STEMM-CCS). The interconnectedness of the ocean and broader planetary system also results in a requirement to undertake such experiments globally, whether using UK infrastructure or international collaboration. Moreover, the design of such experiments and the required associated observational infrastructure is often necessarily iterative and hence can spread across multiple individual collaborative projects and multiple years (Stommel 1963). Collaboration will also remain crucial in enabling access to highly specialised observational infrastructure. For example, access to university, national and international infrastructure (e.g. drill ships) has made the UK a world-leading nation in paleoclimate studies and has ensured our leadership in programs such as IODP. Indeed, such research provides perhaps one of the largest scale example case study in the interconnections of infrastructure components, as underpinning *in-situ* modern oceanographic sampling, identification of sampling, coring and drilling sites through geophysical imaging of the seabed and sub-seafloor, alongside ultimately acquiring the physical sediment and rock cores, requires a wide diversity of methods and platforms to be utilised, sometimes over an extended time period.

4.5.3. Digital Infrastructure

A robust and adaptive digital infrastructure will be required to enable the advances outlined above. Moreover, technological advances in data acquisition, and analysis driven in other areas of science and other sectors, will continue to influence digital capabilities. The likely continued proliferation of a broader variety of high throughput sensors hosted on different platforms, alongside increasing adoption of specific methods which can produce very high-density data from individual samples (e.g. omics and organic mass spectrometry techniques) will increase these requirements for a robust digital infrastructure. Such a supporting digital infrastructure should facilitate the production of findable, accessible, interoperable and reusable (FAIR) datasets. The accessibility, quality control and auditability of data can be especially important in the context of climate change for both scientific and broader political reasons. In addition to the flow of data from measurement / observation system to information use by the science community, digital tools may enhance the onward value chain towards understanding and subsequent broader societal use and impact (Visbeck, 2019).

The digital infrastructure should also support enhanced two-way communications beyond data streams, enhancing command and control capabilities through, for example, edge computing in platforms and sensors which could improve real-time data use to support both autonomous and remote decision making (Lermusiaux *et al.*, 2017). Similarly, advance in remote presence technologies are likely to become more widely available.

As in many other areas, new digital tools, including machine learning and artificial intelligence, will be key enablers. As well as facilitating the processing, analysis and interpretation of specific large datasets (e.g. image recognition and classification), these tools will likely increasingly be used in the more integrative merging of diverse data types, as well as in the automation of often time-consuming data quality control. AI techniques which are being used for weather prediction are also beginning to be used to generate ocean emulators (e.g., Cui *et al.*, 2025; Dheeshjith *et al.*, 2025).

Despite the increasing power of AI enabled methods, there will remain a requirement for numerical models built around partial differential equations, both to directly address scientific questions over a broad range of processes and time and space scales (e.g. UKESM, ERSEM, PISCES, cGENIE) and to ensure predictions are underpinned by demonstrable system understanding. Ocean General Circulation Models (OGCMs) incorporating biogeochemical processes are well established but will continue to represent a broader set of biological components and biogeochemical processes, enabling further investigation of climate feedbacks and impacts. Modelling tools based around, for example, trait-based approaches or Digital Twining may enable assessment of a broader range of potential ecosystem responses as well as identifying climate and ocean tipping elements and points. Effective development and use of such state-of-the-art models will require robust comparison and, in some cases, (e.g. Digital Twins) direct assimilation of diverse data sets which are matched to the complexity, time and space scales. Earth system models incorporating dynamic biological systems, anthropogenic influences, and socioeconomic factors are also being developed and can support evidence-based decision making and climate resilience. Together, these capabilities will underpin a future marine science framework that is predictive, adaptive and integrated.

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4.7. Annex

Table 4.2 Proposed additional EOVs.

	Physics	**Biochemistry**	**Biology and Ecosystems**
Additional Key State Variables	Ocean bottom temperature	Trace metal concentrations	
		Particle size	
		Inherent Optical Properties	
Additional Rates and Fluxes	Radiance/Irradiance (spectral, angular resolved)	Biological uptake/production of key elements and organic and inorganic compounds listed in EOVs (e.g. O_2, organic C, calcification, nitrogen fixation, biogenic silica production)	Biological Growth
		Remineralisation (of carbon and other elements/compounds)	Ingestion/grazing
		Fluxes of key EOVs	Egestion/faecal pellet production
Experimental Parameters		Maximum rates (growth, feeding, etc.)	
		Minimum rates (e.g. baseline respiration)	
		Dependence of rates on key EOVs (e.g., T, O_2, nutrients, light, particle concentration)	
Paleo Proxies		Proxies for key EOVs and rates from the paleo record	

Chapter 5: Protecting Biodiversity and Ocean Health

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5.1. Scope and Context

According to the Convention for Biological Diversity (CBD), biodiversity is the variety of life on Earth at all levels of biological organisation, including ecosystems, species, and genes. A primary cause of the biodiversity crisis is accelerated anthropogenic-driven change through habitat degradation, biological resource overexploitation (fishing primarily), pollution and climate change (Jouffray *et al.*, 2020; Rogers *et al.*, 2022). It has been estimated that 80% of the direct economic benefits from the ocean, worth approximately £211 billion to the UK (ONS, 2021), are dependent on a healthy ocean (Hoegh-Guldberg, Northrop and Lubchenco, 2019). Understanding the distribution of life in the ocean, how it maintains ecosystem functions and how ultimately these underpin human society, are science priorities to provide the knowledge required to manage a transformation from biodiversity and health decline to recovery.

Over 3 billion people globally rely on fish as a primary source of protein but more than 33% of stocks are being fished at unsustainable levels. In addition to threats to food security, biodiversity loss resulting from anthropogenic impacts such as harmful changes in ocean use, introduce direct pressures on marine ecosystems and the services they provide. The Global Assessment Report on Biodiversity and Ecosystem Services (IPBES, 2019) projects that, with the current rate of species loss, 1 million species will be extinct within decades, resulting in a 6th mass extinction event (in effect a massive regime shift). This report (IPBES, 2019) also projects that transformative change can lead to the attainment of conservation target metrics defined by the Convention on Biological Diversity by 2050, and it documents that conservation investments in recent years have resulted in a 29% decrease in extinction across mammals and bird species. Sustainable aquaculture operations are expanding globally to meet demand, yet the potential climate and other impacts on the industry, including declining oxygen and increased harmful algal blooms, remain unpredictable.

The importance of marine biodiversity and the ecosystem services it supports have been recognised in the UN Sustainable Development Goals (e.g. Zero Hunger [2] and Life Below Water [14]) and the UN Decade of Ocean Science for Sustainable Development. Of the 23 international agreements and conventions that existed prior to 2023, no less than 18 require sustainable management of living resources, sustainable management of unexploited species and/or monitoring of species, habitats or the environment (Rogers *et al.*, 2022). Several recent developments in international ocean governance provide a new framework for conservation and restoration of marine ecosystems and species. These include the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction (United Nations, 2023) and the 2023 Kunming-Montreal Global Biodiversity Framework. The former provides a comprehensive legal framework for the conservation of marine biodiversity in areas beyond national jurisdiction. This means that, for the first time, the entire ocean can be subject to conservation measures including marine protected areas (MPAs) and other effective area-based conservation measures. The latter provides targets for protection of 30% of representative ecosystems by 2030 (30 by 30 initiative) as well as restoration of 30% of degraded ecosystems by 2030. Both these and previous international agreements will require knowledge to underpin decision-making for implementation (Rogers, 2024) and, given the UK is a signatory to many of these agreements, significant input by the UK science community.

Despite a long-held recognition of the importance of biodiversity in the marine environment and the need to protect it, the scientific community faces significant challenges in observing and monitoring marine biodiversity over the full taxonomic, spatial and temporal ranges needed to understand the distribution of life in the ocean, its functions, vulnerabilities and resilience (Rogers *et al.*, 2022). These challenges arise from the size of the ocean (1.3 billion km^3 of water), that much of it is remote and extremely challenging to sample (e.g. the open ocean and deep sea), and that marine life is difficult to observe using remote and autonomous systems other than at the surface (Rogers *et al.*, 2022). Our understanding of fundamental aspects of science, such as the relationship between biodiversity and ecosystem function is rudimentary, and knowledge of how to restore marine ecosystems in its infancy (Rogers *et al.*, 2022). Humankind has barely tapped into the vast resources of the ocean genome that have evolved over four billion years and may help to solve many challenges we face today (Blasiak *et al.*, 2020).

However, before we can evaluate the impacts anthropogenic changes or policy changes on biodiversity, it is critical that we define the key measures and characterise the current, or baseline, range of natural variability. This helps in identifying trends, such as species decline or habitat degradation, which are essential for creating effective marine management and conservation policies, allowing us to set realistic targets and measure the success of ocean health initiatives. Baseline data supports scientific research by providing a foundation for studies on marine biodiversity and helps in understanding the natural state of ecosystems and the factors that ultimately influence biodiversity. This concept, however, is made more complex by the shifting baseline triggered by climate change and human impacts on the ocean.

The UK has a reputation for supporting long-term, large-scale biodiversity surveys, such as the Continuous Plankton Recorder (CPR) Survey – the longest running, most geographically extensive marine biological survey in the world – and biodiversity reference sites such as the Western Channel Observatory (WCO), which has been running for over a century. Long-term monitoring of changes in populations of deep-sea species has been achieved at the Porcupine Abyssal Plain Sustained Observatory at 4,850m depth and has demonstrated how deep-sea ecosystems respond to interannual variation in surface primary production. More recently, the Darwin Tree of Life Project aims to sequence the genomes of 70,000 species in the UK and Ireland, including marine species such as cetaceans and fish (see https://www.darwintreeoflife.org/).

The UK government has committed to international marine biodiversity protection efforts, such as signing the Biodiversity Beyond National Jurisdiction (BBNJ) Agreement and pledging funding for marine protection and ocean research (https://www.gov.uk/government/news/uk-pushes-protections-for-international-marine-biodiversity). As a nation, we have world-class expertise and the capacity and infrastructure to enhance our understanding and management of marine biodiversity in the global ocean; this is critical for the sustainability of our planet.

5.2. Anticipated Scientific Developments by 2040

Ocean ecosystems continue to be impacted directly by human activities (e.g. overexploitation) and by climate change, with changes likely to have broad-ranging impacts, including but not limited to species range shifts (i.e., contraction, expansion or both), biodiversity loss, changes in benthic and pelagic fisheries, loss of habitats, and unknown changes to the efficiency of the biological carbon pump. There is also the emerging threat of new anthropogenic endeavours, such as deep-sea mining, which may significantly impact the full extent of the water column, from physical and chemical disturbance of the abyssal seafloor (through habitat destruction and the release of metals), to the mid-water column (through the release of the dewatering plume), up to the surface (where the mining vessel will be emitting noise and light).

While methods for observing ocean biodiversity elements and indicators are in many cases still labour-intensive, technological advancements over the last 10-20 years have significantly enhanced our capacity to make biological and taxonomically resolved observations in the global ocean over a range of organismal and geographical scales (e.g. flow cytometry, optical plankton identification, the use of autonomous platforms video, active and passive sonar, environmental (e)DNA, as well as artificial intelligence [AI] and machine learning [ML] for identification and classification from images, for example in high-throughput imaging [HTI]). Despite these technological advancements, a recent report on the European Ocean Observing Community (Hassoun *et al.*, 2024) has identified specific gaps in the collection of biodiversity data. These included slow progress in the adoption of up to date, fit for purpose observing technologies for biodiversity (e.g. environmental eDNA and other high throughput methods), and a continued reliance on labour-intensive methods, especially in open ocean regions; lack of coordinated basin-scale observations for harmful algal blooms (HABs) and jellyfish blooms, which can have important economic impacts, particularly with respect to fisheries and aquaculture, but also tourism; insufficient coordination and standardization of data (i.e. data is often not FAIR [Findable, Accessible, Interoperable, Reusable] thereby impeding sharing and reuse). There is also a need to train taxonomists to characterise and identify species both in classic methods and emerging technologies. Functional trait analysis can be used in place of taxonomic ID as it focuses on organisms' ecological roles and function rather than identity alone. These can be identified by imaging and/or genetic methods and are particularly convenient when taxonomic work may be arduous, or the expertise is not available, and are considered important when developing Ecosystem-Based Management (EBM) approaches (Nemani *et al.*, 2024).

Addressing these gaps and thus making the best use of current state-of-the-art technologies, will yield significant improvements in observing capacity for ocean biodiversity and health indicators, and support the expansion of existing technological capacity, as well the continued development of new observing tools (in particular, *in-situ* sensors and samplers).

5.2.1. Plankton and Ocean Processes

Internationally, efforts are underway to expand taxonomically resolved observations of ocean biology and biodiversity in the open ocean through the Bio-GO-SHIP (Clayton *et al.*, 2022) and BioGeoScapes (Saito *et al.*, 2024) programmes, with a strong focus on combining 'omics observations with bio-optics, flow cytometric and imaging technologies to link species distribution and metabolic activity to the physicochemical environment. These observing programmes are supported by parallel efforts to standardise and share taxonomic data (e.g. MBON, OBIS, ODIS, OBON). On more regional scales, the development of coastal HAB observing and monitoring networks built on a combination of *in-situ* cell imaging, 'omics and Unmanned Aerial Vehicle (UAV) observations, serve to demonstrate how state-of-the-art ocean biological observations can feed into operational forecasting and warning systems for HABs (Ruiz-Villarreal *et al.*, 2022).

These expansions in biodiversity observing capacity feed into concurrent advances in biogeochemical and ecological modelling applications, for example, for inferring species distributions, forecasting the strength of the biological carbon pump and providing sub-seasonal HAB forecasts, amongst a wide range of policy-relevant and basic science applications. These advances necessitate strong links and communication between data producers, data managers and repositories, and model developers. Increased emphasis on ML and AI-based model frameworks that combine *in-situ* and remote sensing observations to extrapolate and project biodiversity indices in time and space will reinforce the need to develop robust best practices for observational technologies, data management and easily navigable sharing pipelines, to ensure that the maximum value and utility can be extracted from all types of *in-situ* observations.

5.2.2. The Coastal Ocean

In many respects, human impacts are most intense in the coastal ocean where multiple sectors of human activity are competing for space. In addition, climate change is also affecting the coastal zone and may act synergistically with other human impacts. These direct and indirect impacts lead to habitat destruction, mortality and disturbance of marine life, as well as destruction to aquaculture and fisheries resources. Already, a range of technologies are being deployed for observation and monitoring of marine species, habitats and ecosystems. These include remote sensing using satellites, aircraft and unmanned aerial vehicles (UAVs), particularly for habitat mapping (e.g. of coastal wetlands), understanding of ecosystem health (e.g. assessment of mass coral bleaching), as well as patterns of human activity that affect the ocean (e.g. fishing). Sensors can include a range of optical, multispectral (e.g. MODIS, LANDSAT, IKONOS) and hyperspectral sensors, LIDAR, infrared, microwave radiometers, synthetic aperture radar and altimetry (McCarthy *et al.*, 2017; Muller-Karger *et al.*, 2018). In many cases, it is useful to ground-truth such data using direct human observation/survey, but this can be achieved with volunteers in some cases (e.g. for coral reefs; McCarthy *et al.*, 2017).

Establishing baselines for marine biodiversity in the coastal zone, including the breeding, foraging and migratory corridors of charismatic megafauna, as well as fisheries resources are essential elements of marine spatial planning. They are also critical for the conservation and restoration of marine biodiversity through the use of Area Based Management Tools (ABMTs) or other measures. In addition, such survey and monitoring studies are important to understand the physical and biogeochemical drivers of distribution of marine species and the communities they are part of. Scientific study of coastal ecosystems is also important in understanding their function and ecosystem services to humankind (e.g. carbon sequestration and storage).

Seafloor bathymetry can be obtained using multibeam or side-scan sonar, with backscatter data useful in mapping seafloor texture which can correspond to either the physical nature of the seafloor (sediment versus rock) and/or the presence of biological communities (e.g. coral reef; Harris and Baker, 2012). Traditionally, this would be collected by surface vessels with sonar attached to the hull or towed. The use of autonomous surface or underwater platforms is now becoming more common for such surveys. Benthic communities are increasingly surveyed using video imagery deployed by SCUBA divers (for shallow waters), drop cameras, including Baited Remote Underwater Video (BRUVs), towed camera systems or autonomous underwater vehicles (Mallet and Pelletier, 2014; Williams *et al.*, 2016). Advances in sensors for environmental parameters, as well as positioning systems, have greatly assisted the accurate mapping of seafloor communities and environmental drivers of distribution. Such methods generally only provide data on epibenthic megafauna visible in photographs or video. Camera resolution has increased over time and therefore such surveys can generate large quantities of data with challenges in extracting scientific information from hundreds of hours of video. Machine learning is being adopted to assist in rapid identification of organisms from such video data (e.g., Beyan and Browman, 2020).

Environmental DNA (eDNA) methods have now been tested sufficiently to demonstrate that they can provide a new and useful tool for identifying the presence of species (e.g., Lacoursière-Roussel *et al.*, 2018; Carvalho *et al.*, 2019; Merten *et al.*, 2023; Dukan *et al.*, 2024). The combination of such tools with citizen science to collect samples can provide large-scale synoptic data on the coastal diversity of fish and other organisms in the nearshore zone (Agersnap *et al.*, 2022). In some cases, eDNA data can be semi-quantitative providing some idea as to the relative abundance of species present (Dukan *et al.*, 2024). However, eDNA approaches can be biased in their representation of different taxa and it has been found that they can be used as a complementary form of sampling alongside other sampling approaches to provide a more complete picture of biodiversity present (Leduc *et al.*, 2019). However, even when sampling from challenging communities, such as infaunal invertebrates, eDNA approaches can detect significant correlations between species diversity and human impacts (e.g., Lanzén *et al.*, 2021). Thus, as a monitoring tool, such methods can offer more rapid and cost-effective means of detecting change in coastal marine ecosystems. Smaller organisms, such as meiofauna, are more tractable to automated sorting of samples, DNA metabarcoding and image-based identification techniques. The use of optical particle counters can dramatically increase the speed of sorting such organisms from sediments and thus their identification for scientific or monitoring purposes. A limitation to eDNA methods can be the lack of ‘known’ sequences in DNA barcoding databases, meaning that many sequences are only attributable to higher taxonomic categories (genus, family, order or even higher; Rogers *et al.*, 2022). Other issues concern methodology and consistent sampling strategies (discussed in (Rogers *et al.*, 2022). To combat this, through the coupling of automatic sorting and imaging to DNA fingerprinting, we can directly feed into open access repositories (Foulon *et al.*, 2025). Furthermore, recent tests of the large particle sorter and imager COPAS VISION[1] represent an exciting opportunity in the study of meiofauna.

Active sonar is routinely used in fisheries stock assessments and in analysis of the ecology and behaviour of pelagic organisms in the coastal zone. Passive sonar is routinely used to detect the presence of sound-producing animals, most notably cetaceans, but also other organisms such

[1] https://www.unionbio.com/copas/vision.aspx

as fish and marine invertebrates such as alpheid shrimp (e.g., Mooney *et al.*, 2020). In both cases, use of machine learning offers the possibility of assisting in classification of organisms from their acoustic signatures, greatly accelerating data analysis and increasing resolution.

By 2040 we expect that mapping, classification and monitoring of coastal communities will be more automated, using remote sensing or automated platforms to gather data. Image-based and acoustic data are likely to be classified through the use of machine-learning algorithms leading to more rapid interpretation of data. EDNA and metabarcoding-based approaches will become successively more useful for assessment of species presence in ecosystem monitoring as methods are perfected, challenges of statistically valid sampling overcome and barcoding libraries better populated. The prospect of development of lab-on-a-chip eDNA sampling and even on-board sequencing are particularly exciting areas at present and in the future.

5.2.3. The Deep-Water Column

The ocean between the surface and the deep seafloor is the least explored and largest ecosystem on Earth. It's size and the technical challenges of working at high pressures mean that sampling and observing this environment is challenging. Attention has been drawn to the deep-water column because of the recognition that the mesopelagic zone (200m – 1,000m depth), in particular, is important in the transport of particulate organic carbon from the surface into the deep ocean where it is sequestered potentially for millennia. Transport occurs through the passive sinking of particulate organic matter (marine snow) or through repackaging or active transport of carbon through biological activity (predation, faecal pellet production, diurnal vertical migration; Cavan *et al.*, 2019). States and fishing companies are also assessing the prospects of fishing mesopelagic ecosystems as they comprise an overall high biomass of fish globally (Hidalgo and Browman, 2019). Whilst scientists have only recently identified the scale of biomass of mesopelagic organisms (e.g. Kaartvedt, Staby and Aksnes, 2012), some elements of the ecosystem remain challenging to quantify (e.g. gelatinous zooplankton) and processes difficult to measure (Cavan *et al.*, 2019). Knowledge of biodiversity declines with depth, such that bathypelagic and abyssopelagic ecosystems remain poorly characterised.

Estimation of the rain of particulate organic carbon (POC) into the deep sea has traditionally been studied using sediment traps (Cavan *et al.*, 2019). However, estimation of POC fluxes in the mesopelagic has advanced with the development of free-drifting sediment traps and optical and autonomous devices (Cavan *et al.*, 2019). Optical devices in particular are capable of generating large amounts of data on particle distribution, as well as the distribution of plankton (Cavan *et al.*, 2019; Hoving *et al.*, 2019). Development of *in-situ* devices for experimental measurements of particle remineralisation rates indicate the power of autonomous platforms for measurement of processes without artefacts arising from recovery of material onto vessels for incubation experiments (e.g. Boyd *et al.*, 2015). The study of zooplankton, micronekton and nekton has traditionally been done using nets, acoustics and imaging (Haddock and Choy, 2024). Net sampling has strong bias introduced by net avoidance. selectivity of net mesh size, and destruction of delicate organisms, yet it brings the advantages of enabling larger numbers of specimens to be collected and analysed for age, size, trophic position, pollutant content (e.g., microplastics and heavy metals). New net systems that utilise camera and senso systems to aid targeted sample selection have also been developed to protect ecosystems that are targeted by net fisheries. Acoustics have the advantage of providing a large-scale view of the presence, behaviour and to some extent biomass of mid-water organisms. However, the return from different organisms varies widely and it only gives a rough categorisation of the organisms detected (Haddock and Choy, 2024). ROVs have provided new information on the spatial and temporal distribution, behaviour, physiology and trophic relations of mesopelagic and bathypelagic species (e.g. Robison, Reisenbichler and Sherlock, 2017). Many of these advances have been achieved through time series surveys but also through the capture of the delicate animals of the deep-water column and aquarium-based (mesopelagic only) and *in-situ* measurements and experiments (Robison, Reisenbichler and Sherlock, 2017). However, they have the disadvantage that they must be supported by a surface vessel (Haddock and Choy, 2024).

By 2040 it is expected that automated platforms and systems will be playing a much greater role in studying the biodiversity of the deep-water column. Autonomous platforms, equipped with high-resolution cameras and biological acoustics such as MBARI's Dorado AUV (Robison, Reisenbichler and Sherlock, 2017) and the buoyancy-controlled lagrangian drifting platform Driftcam (Berkenpas *et al.*, 2018) provide useful ways to survey the deep-water column and can be launched from relatively small vessels. Further development of AUVs and lagrangian drifting platforms with the addition of a range of sensors in addition to cameras and sonar are likely to increase understanding of processes such as particle flux and remineralization. As with inshore studies, eDNA is being demonstrated to be useful for identification of mesopelagic fauna but also appears to have different sampling bias to net samples (Govindarajan *et al.*, 2023). It has been suggested that such an approach (as with coastal studies) is therefore best used in a complementary fashion to traditional net sampling. We would see the potential to combine eDNA sampling with AUVs or drifters to give a more complete picture of deep-water column diversity. One great advantage of eDNA sampling is that it can detect fast swimming or large megafauna that are not sampled using deep-water nets (e.g. tuna and cetaceans; Govindarajan *et al.*, 2023). For some purposes, such as *in-situ* experimentation and capture of specimens for a range of studies such as dietary analysis and physiology intervention will still be required using nets or ROVs deploying sophisticated sampling equipment.

A recent observation that the bio-optical sensors to measure chlorophyll a fluorescence (fchl), backscattering at 700 nm (bb), and fluorescent dissolved organic matter (FDOM) (fluorescence by coloured dissolved organic matter) mounted on Argo floats may attract organisms in the deep-water column and cause spikes in data when they interact with the equipment (Haëntjens *et al.*, 2020). Analysis of net samples from the depths where data spikes are observed suggest the interacting organisms could be copepods, euphausiids, lantern fish, and/or bristlemouth fish (Haëntjens *et al.*, 2020). The study indicates that ARGO floats and other instruments (e.g. gliders) carrying bio-optical sensors may be able to provide some quantitative data on elements of migrating and non-migrating deep water column organisms (Haëntjens *et al.*, 2020).

5.2.4. The Seafloor

The deep seafloor comprises vast abyssal plains of fine sediment as well as a range of ecosystems that are more challenging to survey and sample such as canyons, seamounts, mid-ocean ridges, fracture zones, and trenches. Typically, the fauna, which varies in size from megafauna (visible in cameras down to 2cm), macrofauna (animals from 1cm to <1mm retained in a sieve size of 250 μm) and meiofauna (animals that are retained in a mesh sieve mesh size of 32 μm) includes a high proportion of undescribed species and so integrated taxonomic approaches can be an important aspect of deep benthic studies. Traditionally, work on deep-sea benthic biodiversity has used over-the-side sampling technologies such as dredges, trawls, sleds, box-corers and multicorers which have allowed a shift from qualitative data collection to quantitative data collection (Rogers and Ramirez-Llodra, 2024). The development of deep-submergence technologies, such as drop- and towed-cameras, submersibles and ROVs has allowed a broader range of deep-sea ecosystems to be surveyed and sampled and have led to the discovery of habitats such as deep-sea hydrothermal vents, hydrocarbon seeps, cold-water coral reefs and other vulnerable marine ecosystems (VMEs; Rogers and Ramirez-Llodra, 2024). Even these technologies have been generally limited to depths <6,000m and more recently the investigation of hadal ecosystems has generally been undertaken using landers and most recently a new type of submersible (Jamieson *et al.*, 2009; Jamieson, Ramsey and Lahey, 2019). An issue related to all these sampling technologies has been the legacy of undescribed deep-sea species which are collected using such technologies, but which remain in Museum and other collections undescribed for many decades, impairing understanding of deep-sea biodiversity.

In the coming decades, surveys of deep-sea megafauna, possibly coupled with eDNA sampling may be achieved using autonomous underwater vehicles. The conversion of underwater images collected using such technologies to useful data will be greatly assisted by automated annotation methods based on machine learning/AI (see above). Application of this technology is still not straightforward and algorithms for machine learning will require further improvement. For small organisms living on or in deep-sea sediments there is unlikely to be an alternative to sampling of seafloor sediments using corers deployed from the surface or from ROVs or submersibles. However, more rapid sampling and classification of meiofauna from sediment samples using flow cytometry and subsequent identification of organisms using 3D-imaging and eDNA approaches is currently in development. Macrofauna will be more challenging and integrated taxonomic approaches using a combination of DNA sequencing (DNA barcoding) alongside 3D imaging using light microscopy or micro-CT may offer the potential to speed up species classification. As with coastal habitats, eDNA-based metabarcoding approaches may deliver the potential to reach a much better understanding of the global distribution of deep-sea benthic organisms, including addressing of long-standing questions relating to species range and species turnover with increasing distance between samples. Early studies have confirmed that environmental metabarcoding of deep-sea sediment can detect a high diversity of operational taxonomic units (OTUs) but many of these have remained unassignable to known taxa or their closest relatives have been shallow water species (e.g. Lejzerowicz *et al.*, 2021; Cordier *et al.*, 2022). This likely arises from lack of representation of deep-sea taxa in barcoding databases. Whilst this may not be relevant to answer some ecological questions as well as in the monitoring of deep-sea ecosystems for change in response to disturbance, it will be a barrier to higher resolution ecological science. Again, integrated taxonomic approaches will be required to fill in such gaps in knowledge. Some deep-sea ecosystems will remain difficult to study by virtue of the extreme remoteness (e.g. trenches) or the complexities of sampling from them (e.g. the macrofauna inhabiting rocky seafloor).

5.2.5. Biodiversity Data and Ocean Modelling

In parallel with technological advances in biological observing technologies, the last decade has seen a step change in the use of numerical and statistical models, data assimilation and ML tools to develop predictive capacity in ocean and climate conditions and how they may interact with biodiversity over a range of spatial and temporal scales. These initiatives rely on the availability of robust data pipelines, open data sharing and ultimately funding support for proper data management and storage. A number of biodiversity databases exist providing information useful for monitoring, assessment, projection and management. Examples of these include the World Register of Marine Species (WoRMS; species taxonomic information), the Ocean Biodiversity Information System (OBIS; species occurrence data), International Nucleotide

Sequence Database Collaboration (INSDC; DNA sequence data) as well as more general databases for environmental and other forms of data (e.g. Pangaea; Rogers *et al.*, 2022). These databases vary in size and integration, with some being large, well-supported and highly integrated whereas taxon-specific databases can be small and supported by a few experts (e.g. Brachiopod Database). Database resources are therefore substantial but often fragmented and tailored to specific user communities (Rogers *et al.*, 2022). Any future expansion in the breadth and volume of ocean biological observations must be matched by support for the development of the data management infrastructure needed to disseminate and serve these data streams to the widest possible range of stakeholders, end users and data product developers. This will require greater connectivity and interoperability of databases (Rogers *et al.*, 2022). Ongoing efforts towards achieving data democratization, along with a lower bar to entry for data manipulation and visualisation tools will support clearer and more compelling sharing of knowledge, cross-disciplinary communication, the translation of information into actionable insights, and co-design of science and policy actions to support ocean health and biodiversity, and drive impact opinion beyond the scientific community.

5.3. Key Science Questions, Knowledge Gaps and Uncertainties

Here we highlight key knowledge gaps identified through a series of community discussions and consultations.

5.3.1. Benchmarking Ecosystem Function and State

How is life distributed in the ocean, what are the global patterns of species distribution and biodiversity, and what are their drivers?

There are large regional gaps in our baseline understanding of the distribution of marine species, particularly in the southern hemisphere, (e.g. Righetti *et al.*, 2020 shows dearth of phytoplankton data from OBIS and other repositories in the Indian Ocean and South Pacific in particular; see also Rogers *et al.*, 2022). Gaps in data and understanding tend to increase with increasing distance from land and increasing depth. The lack of knowledge in baseline biodiversity data undermines our ability to understand the responses of biodiversity to ocean change at a range of scales including to both direct (e.g. overfishing) and indirect (e.g. climate change) impacts.

How can we preserve ecosystem function and connectivity to maintain ocean health and prevent biodiversity loss in the face of a changing environment?

This requires understanding of patterns of connectivity between populations of marine species, interdependence between species and communities and their annual and interannual variation. Understanding of connectivity is critical to modelling and predicting the response of species, and communities to human impacts, especially climate change where changes in physical oceanographic parameters are driving the migration of species towards the poles. Connectivity is an important element in the design of networks of marine protected areas (MPAs) which are an important tool in maintaining and monitoring biodiversity, ecosystem function and health.

Can we improve biological health indicators (e.g. biodiversity, connectivity, disease, biomass, reproduction, recruitment, size spectra, phenology, etc…) for species and communities within ecosystems that can be applied widely and benchmark this as a 'state' to understand future change?

Indicators are important in detecting changes in healthy ecosystems in response to local and global stressors and providing managers and policymakers with information to assist in development of management measures to improve environmental status and support ecosystem service provision (e.g. Rombouts *et al.*, 2013; Tett *et al.*, 2013; Borja *et al.*, 2016). Indicators should be cost effective and provide measures that reflect or synthesise the status of important aspects of ecosystem structure and function (Borja *et al.*, 2016). Whilst many indicators have been developed, they are often specific in geographic application or to specific taxa or elements of ecosystems (e.g. Rombouts *et al.*, 2013). Better and more universal indicators are required that, when integrated with modelling can identify changes in marine ecosystems, impacts on ecosystem resilience and function and the specific drivers of change. Models can also offer the potential of expanding the geographic scope of measurements of indicators at smaller geographic scales as well as explore the potential benefits of different management approaches. Modern tools such as environmental metabarcoding are providing higher resolution indicators encompassing biological communities.

5.3.2. Organismal Function and Environmental Change:

How does the biodiversity, structure and function of marine ecosystems influence biogeochemistry in a changing ocean?

A healthy marine ecosystem is self-maintaining, vigorous, resilient to externally imposed pressures, and able to sustain services to humans. It contains healthy organisms and populations, and adequate functional diversity and functional response diversity. All expected trophic levels are present and well interconnected, and there is good spatial connectivity amongst subsystems (Tett *et al.*, 2013). In the context of a changing ocean this raises a number of questions relating to ecosystem resilience and maintenance of critical ecological functions. For example, to what extent do different species and taxonomic groups have the capacity to respond to environmental and ecosystem change through phenotypic plasticity and/or adaptation? In phytoplankton communities, how are physiological (e.g. primary production, N_2 fixation) and ecological (e.g. grazing, viral infection) rates modulated by physicochemical conditions (e.g. temperature, pH, nutrients and species diversity)? How will the interactions between species in ecosystems change in the context of a changing climate? How do trophic interactions impact the biological carbon pump, dissolved oxygen concentrations, or trophic transfer?

What are the underlying genomic and evolutionary mechanisms behind phenotypic plasticity and long-term adaptation to environmental variability and long-term environmental change?

Climate change is altering many physical parameters of the ocean including temperature, elements of the carbon system and declining oxygen levels (Kelly and Griffiths, 2021). Simultaneous multivariate changes in the environment pose a significant challenge for marine species. These are even more complicated because many marine organisms have biphasic life histories involving separate larval and adult phases subject to different environments (Kelly and Griffiths, 2021). Marine species, other than those living in very variable environments, such as the intertidal zone, are likely to be living at the limits of their physiological tolerances as temperatures and other parameters vary little through the year (Kelly and Griffiths, 2021). Responses to such changes are likely to involve a complex interplay between phenotypic plasticity and evolutionary change at the genomic level (Reusch, 2014). Organisms like phytoplankton, responsible for most primary production in the ocean, have short generation times and large effective population sizes and are therefore likely to exhibit some adaptation to climate change with potential significant consequences for global carbon cycling (Kelly and Griffiths, 2021). For longer lived species phenotypic plasticity may be important to "buy time" for adaptation to take place. Investigation of the roles, responses and outcomes of phenotypic and adaptive responses to climate change require a combination of experimental approaches, field observations and modelling (Reusch, 2014; Kelly and Griffiths, 2021).

5.3.3. Resilience and Macroecological Responses to Change:

How resilient are species and communities to environmental change and human pressures?

The definition of resilience tends to implicate a marine ecosystem that is resistant to change, or which is able to return / recover to a baseline state or recover to a state where ecosystem functions and services are maintained (Mumby *et al.*, 2014). These forms of resilience are different and may have different implications for the species and communities within ecosystems (Mumby *et al.*, 2014; O'Leary *et al.*, 2017). For example, an ecosystem with a high level of functional redundancy may lose species but maintain important ecosystem functions and services to human society. This seems to be linked to ecosystem biodiversity, trophic structure and functions, especially those involving feedback loops to maintain ecosystem stability. Evidence suggests that resilient ecosystems are often characterised by high levels of connectivity whereby larval / propagule recruitment is an important factor in ecosystem recovery (O'Leary *et al.*, 2017). In other cases, high levels of functional interactions between species can support ecosystem resilience enabling important feedback loops that maintain ecosystem stability (O'Leary *et al.*, 2017). The physical environment itself can provide protection for ecosystems from environmental change (e.g. upwelling of cold-water preventing mass bleaching on coral reefs; O'Leary *et al.*, 2017). Other factors include genetic variation, functional redundancy, and remoteness from human disturbance (O'Leary *et al.*, 2017). Factors that can decrease the resilience of marine ecosystems to climate impacts include local anthropogenic stressors, the occurrence of multiple stressors as well as failures in management of human activities (O'Leary *et al.*, 2017). Many questions remain about how resilience occurs in marine ecosystems and how it is undermined and the implications for ocean management and future ecosystem services. These require a combination of field-based observations, manipulative experimental approaches and modelling.

Is it possible to better predict ecological tipping points or regime shifts where environmental thresholds are crossed, and ecosystems undergo a rapid change to an alternative state?

Tipping points or regime shifts are where there is a rapid change in ecosystem organisation to a new stable configuration that generally results in negative impacts on ecosystem service provision and thus society (Hewitt and Thrush, 2019; Carrier-Belleau *et al.*, 2022). These changes can often be detected across multiple ecosystem components and have been seen in many ecosystems including coral reefs, kelp forests and in fisheries such as northwestern Atlantic cod. They are characteristically difficult to predict (Hewitt and Thrush, 2019). Typically tipping points or regime shifts occur as a result of synergistic interactions of multiple drivers / stressors on communities / ecosystems (Carrier-Belleau *et al.*, 2022). They can be linked to extreme events of stress, such as marine heat waves (Carrier-Belleau *et al.*, 2022). Stressors can influence different elements of ecosystems or different processes and so measuring / observing single or a few aspects of an ecosystem can miss changes heralding a regime shift (Hewitt and Thrush, 2019; Carrier-Belleau *et al.*, 2022). Understanding the potential for tipping points or identifying the warning signs that they may take place requires a whole ecosystem approach. Potentially fruitful avenues of study involve looking across multiple variables for correlated change in communities or ecosystems (Hewitt and Thrush, 2019). A warning sign of impending regime shift can be increased variance in data related to individual species / populations or across communities as well as longer recovery times from perturbations (Hewitt and Thrush, 2019). Ecosystem structure is likely very important in the potential for regime shifts especially related to feed backs and trophic interactions (Hewitt and Thrush, 2019). Trait variation and evolution amongst species and populations may be important in increasing or decreasing the likelihood of regime shifts and changes in traits can lead to destabilisation of population dynamics (Dakos *et al.*, 2019). Modelling of ecosystems can be very helpful in exploring how components are related and what aspects of a community are best to monitor. Both field-based observations and experimental approaches using simplified ecosystems are likely to be required to gain a better understanding of the warning signs and mechanisms of regime shifts (Carrier-Belleau *et al.*, 2022).

5.3.4. Conservation and Management of Biodiversity

What are the main threats to marine biodiversity? Regionally? Globally?

The Living Planet Index (*WWF Living Planet Report: A System in Peril*, 2024) documented that wildlife populations, including those of marine species, have declined by an average of 73% since 1970. Analyses undertaken of the IUCN Red List have indicated that the main causes of species decline are overexploitation (e.g. overfishing and the destructive effects of fishing), coastal development, pollution, climate change, invasive species and transportation (Rogers *et al.*, 2022; see also IPBES, 2019). Whilst some of these threats are well understood (e.g. overfishing of target species) others are not and are changing overtime in the threat they pose or interact with other stressors in a synergistic, or antagonistic manner. Different species, communities and ecosystems are affected by anthropogenic stressors in different ways (e.g. Rogers *et al.*, 2022), and there is an additional risk to undescribed species with unknown responses to environmental impacts.

Faced with such challenges how do we mitigate such threats for the substantial biodiversity present in the waters of the UK and its overseas territories? What are the most effective strategies to conserve biodiversity in the Exclusive Economic Zones of the UK and its overseas territories as well as in Areas Beyond National Jurisdiction (ABNJ) where human activities are increasing? The UK is also a party to many international treaties and agreements which have a requirement to protect and monitor biodiversity; how do we meet these commitments?

How effective are MPAs and how can networks of MPAs be best designed to adapt to the influence of climate change?

The success of marine protected areas has been a controversial topic for some time with many publications pointing to the failure of spatial conservation measures to stem the loss of biodiversity (e.g. Roberts, 2005). Part of this failure has been related to identification of the right parameters to measure and monitor (including knowledge of baseline conditions) to ascertain how well MPAs are achieving their conservation objectives (e.g. Woodcock *et al.*, 2017; Pendleton *et al.*, 2018; Hopkins *et al.*, 2020; Meehan *et al.*, 2020). This requires not only assessment of what is happening within an MPA but also the wider consequences of protection on surrounding socioecological systems (e.g. Agardy, 2018; Pendleton *et al.*, 2018). Reviews of MPA success have suggested that several factors can contribute to success, including complete prohibition of fisheries (no-take reserves), high levels of enforcement, age, size and isolation from human populations (e.g. Edgar *et al.*, 2014). However, this is by no means an exhaustive list. MPA networks are seen as more effective than single protected areas. This is because MPA networks are necessary to maintain habitats that support all life history stages of organisms of conservation concern as well as maintain movement across habitats (Beger *et al.*, 2022). However, connectivity does not only involve movements of organisms but also the flow of energy and materials between ecosystems (Beger *et al.*, 2022). Ecological connectivity also includes the interactions between species such as via food webs. The IUCN have defined connectivity as: The movement of organisms, including their genes, gametes and propagules, between populations, communities and ecosystems, as well as that of non-living material from one location to another (Gardner *et al.*, 2024). Connectivity operates over different scales across oceanographic boundaries and across jurisdictions. Data limitation has been a consistent issue for design of MPA networks but development of physical oceanographic modelling of particle dispersal and habitat suitability modelling, together with data from Earth observation satellites, pattern recognition algorithms, satellite and acoustic telemetry, soundscapes, chemical signatures, gene flow studies and metabarcoding (eDNA) are enabling the identification of connectivity corridors between habitats and ecosystems (Gardner *et al.*, 2024). Designing MPAs which are resilient to climate change involves considering how ocean currents and physical characteristics such as temperature may change in the future and how this may influence species distribution. Connectivity corridors may be especially important in allowing species to migrate to new geographic areas which match their ecological needs. Protection of source rather than sink populations of individual species may also be very important (Gardner *et al.*, 2024).

What other conservation measures are there and how effective are they?

Other effective area-based conservation measures (OECMs) are geographically defined areas governed and managed to achieve positive and sustained long-term outcomes for the *in-situ* conservation of biodiversity (Gardner *et al.*, 2024). These include many forms of area-based management that have conservation benefits but do not fit within the framework of MPAs (Estradivari *et al.*, 2022). They include measures such as fisheries closures, Locally Managed Marine Areas and systems of traditional ocean customary management implemented by indigenous people (Estradivari *et al.*, 2022). The issue with such measures is that their effectiveness has often been poorly studied so benefits can be unclear and are likely to vary depending on the local factors.

What are the ecological, societal and economic benefits of marine conservation measures and what are the barriers to their implementation?

One of the main barriers to establishment of effective MPAs and OECMs is community/stakeholder engagement (Giakoumi *et al.*, 2018). It is therefore of paramount importance that stakeholders are widely consulted during the development of spatial conservation measures and that such consultation is adequately monitored throughout the process and during the process of implementation. Ecological barriers mainly are concerned with a lack of data on both the species and ecosystems to be conserved as well as the wider network of habitats/ecosystems to be included in a network of MPAs and OECMs (Gardner *et al.*, 2024). Development of approaches that can get around such a lack of data is a research priority. This also points to a lack of scientific observations of the kind needed to establish such MPA networks. Valuation of the monetary and non-monetary values of ecosystems can also assist in their implementation. In terms of climate change MPAs and OECMs are beneficial in many ways including, potentially, climate mitigation through carbon sequestration and acidity buffering, and climate adaptation through both ecological and social benefits (Jacquemont *et al.*, 2022). Such benefits can be used to secure financial investment in marine protected areas as nature-based solutions to climate threats with multiple co-benefits for biodiversity and ecosystem function. Much more work is required on understanding the values of natural capital, its benefits to humankind and how this can be used to tap into blue finance to support MPAs and OECMs over the longer term. In a broader sense valuation of natural capital can help with decision making over how to balance and manage the benefits and impacts of human exploitation of marine biotic and abiotic resources.

How do we effectively restore and/or rehabilitate marine ecosystems?

Restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed to its original state (species composition, abundance etc.; Voolstra, Peixoto and Ferrier-Pagès, 2023). In many cases restoration may not be feasible where environmental change has occurred as a result of climate change or direct human impacts such as overfishing or pollution. In such cases rehabilitation may be required whereby to 'future-proof' ecosystems, it is not sufficient to merely restore them to their original composition, but to enhance them through active interventions, such as probiotic provision, environmental hardening, genetic modification or similar measures, in order to promote protection, extend adaptation, and increase resilience (Voolstra, Peixoto and Ferrier-Pagès, 2023). Restoration and rehabilitation of marine ecosystems are mostly discussed in the context of coastal ecosystems such as coral reefs and seagrass beds, although the science of such restorative activities is still in its infancy, especially when considering the large geographic scale over which they may have to be practiced. Significant loss of deep-sea ecosystems such as cold-water coral reef and garden habitats from human activities such as bottom trawling means that these ecosystems also need to be considered for restoration (Liu *et al.*, 2024).

5.3.5. Meeting the UK's International Commitments on Biodiversity

Under international treaties the UK has explicit commitments to biodiversity monitoring, sustainable management, conservation, biosecurity and capacity development with respect to low and middle-income countries (see Part 1). These commitments relate to the UK EEZ, overseas territories and areas beyond national jurisdiction. In some cases, UK biodiversity commitments are undermined by a lack of knowledge of baseline biodiversity, both within national waters but also in terms of UK Overseas Territories and areas beyond national jurisdiction. In other cases, for example, in the designation of Marine Conservation Zones in UK waters, conservation objectives are undermined by damaging human activities within them, such as bottom trawling. The management of marine space demands knowledge of the distribution of species and habitats, especially those which are threatened or sensitive to human activities. The interaction of biodiversity with societal demands for blue economic activity means that biodiversity knowledge must be improved for marine spatial planning and ocean management purposes.

It is also important to emphasise that marine science is an important element of maintaining the UK's position in international governance, sovereignty, and soft power as an ocean superpower. Marine scientific data gives the UK a place at the table at conventions and treaties connected to the ocean, such as the Convention for Conservation of Antarctic Marine Life (CCAMLR), the Convention on Biological Diversity (CBD) and the new Biodiversity Beyond National Jurisdiction Agreement. Capacity development activities through training opportunities especially when implemented through co-production of marine science with researchers from developing countries. Marine biodiversity data is essential knowledge for the implementation and decision making in many international treaties and agreements.

5.4. Observation and Product Requirements

Assessing marine biodiversity requires a comprehensive and systematic approach to capture the complexity and dynamics of marine ecosystems (Canonico *et al.*, 2019), while also prioritising making observations of the variables which provide the most information on the system for science and policy applications (Miloslavich *et al.*, 2018). The foundation of our current understanding of ocean biodiversity is largely the result of a history of ocean exploration and sampling of ecosystems as well as the initiation and continuation of sustained biological time series.

It is critical we remain both agile and adaptable in our approaches. This will require a combination of sustained temporal and spatial observations (note a prioritisation of UK capability on sustained ocean observations has recently been reviewed: https://ocean-observations.uk/); as well as experimental capacity on oceanographic platforms (research vessels and autonomous vehicles – each of which have a spectrum of specific sampling and experimental capabilities suited to different tasks). By addressing these key observational requirements, we can gain a deeper understanding of marine biodiversity and develop effective strategies for its monitoring, conservation and management, potentially mitigating a biodiversity catastrophe as well as mitigating and/or adapting to climate change. **It will be critical to ensure a National Capability for marine biodiversity assessment and science to help accelerate informed decision making to restore the health of our ocean**, including the necessary associated specialist workforce to maintain and deploy the equipment within the infrastructure (e.g., nets, corers, AUVs, ROVs).

It is important to ensure species composition and abundance at all trophic levels are assessed and monitored (i.e. observations are continued and maintained over time). These observations should encompass existing ocean Essential Biodiversity Variables (EBVs)/biological Essential Ocean Variables (EOVs), as well as emerging EBV markers currently being developed to maximise the information provided by eDNA and 'omics sampling.

- Taxonomic Surveys: Regular surveys to identify and quantify species (even if semi-quantitative or absence-presence criteria) in a range of marine habitats (coastal to open ocean; surface to deep ocean; pelagic to benthic). *New surveys should be initiated in under-sampled but economically and/or ecologically significant regions (ideally levering global UN Decade Programmes such as OBON), and/or to address strategically important topics arising in the ocean (e.g. marine carbon dioxide removal), and existing long-running ecological time series must be maintained to provide crucial (but rare) data collections spanning climate change relevant time scales (e.g. > 30-60 years).*
- Genetic Diversity: Monitoring genetic variation within and between species using techniques like eDNA, metagenomic barcoding, genomic skimming approaches, and genomic sequencing. The ocean hosts a wider range of higher taxa than land, a legacy of nearly 4 billion years of life in changing environmental conditions and is therefore important in our basic understanding of how life evolved and the full range of genomic variation that has emerged across the tree of life.

Cross-cutting recommendations are key to ensure environmental drivers (non-biological EOVs and EBVs Frameworks) are developed (Muller-Karger *et al.*, 2018) to include requirements for underpinning environmental information to support research into changes in ecosystems.

- Physical Parameters: Continuous monitoring of temperature, salinity, currents, and other physical parameters that influence marine biodiversity.
- Chemical Parameters: Measuring concentrations of nutrients, pollutants, and other chemical substances in the water.
- Geological Parameters: Critically important for benthic organisms.

There is a need for programmes to understand the fundamental relationships between biodiversity and ecosystem function (Ruhl *et al.*, 2021) – this links to ecological and biogeochemical model development and validation.

- Primary and Secondary Productivity: Measuring the rate of photosynthesis and biomass production in marine ecosystems.
- Nutrient Cycling: Monitoring the flow and recycling of nutrients within marine ecosystems, including carbon, nitrogen, and phosphorus cycles.
- Metabolic activity and potential: e.g. nitrogen fixation, respiration. Physiological adaptation/phenotypic plasticity to changing conditions (this also comes up below).

There is also a need for programmes to determine species interactions and trophic dynamics.

- Food Web Analysis: Studying predator-prey relationships and energy transfer through the food web.
- Behavioural Observations: Tracking the behaviour and movement patterns of key species using tagging and telemetry.
- Other interspecies interactions: the importance of mutualistic, parasitic and competitive relationships in determination of population and community dynamics.
- Rare Species: The significance and role of rare species in marine ecosystems.
- The microbiome and holobiome: Adaptations of healthy species to environmental impacts.

There are specific areas of focus for assessing human impacts.

- Anthropogenic Pressures: Assessing the impact of human activities such as fishing, pollution, deep-sea mining, marine carbon dioxide removal, and coastal development on marine biodiversity.
- Marine Protected Areas (MPAs): Use of digital technologies to improve the design of networks of MPAs considering the effects of climate change. Evaluating and monitoring the effectiveness of MPAs and other conservation measures in protecting biodiversity.

There are a number of ways to improve the science of habitat restoration and rehabilitation.

- Improving habitat restoration technologies so that they may be scaled and applied over ecologically relevant spatial extents.
- Developing science to rehabilitate marine species so that their vulnerability to climate-change stressors is decreased and/or resilience increased. Examples of methods that

might be considered include assisted migration, genetic modification and use of probiotics.

- Habitat restoration for nature-based solutions such as climate mitigation / adaptation which also benefit biodiversity (e.g. coastal protection using natural ecosystems, coastal blue carbon ecosystems such as kelp forests, seagrass beds, mangrove forests and other coastal wetlands).

Science needs to ensure technological and methodological innovations are progressed, including low-cost options.

- Remote Sensing: Utilizing satellite and aerial imagery to monitor large-scale changes in marine ecosystems, including patterns of human use/impacts on the ocean.
- Deep-Submergence Systems: Deploying autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) for detailed exploration and data collection.
- Methodological innovations: For example, in towed camera systems, corers, and net systems. Improvements in these lower-cost systems will enable less affluent institutes and countries to carry out marine biodiversity research and monitoring, alongside those able to afford autonomous vehicle access.
- Data Integration: Combining data from various sources and platforms to create comprehensive and FAIR datasets.
- Machine Learning/AI: Ensure that ML/AI are progressed in marine biodiversity research in fields such as computer vision, ecosystem modelling, MPA design and control of autonomous platforms.
- Animal oceanographers, tagging and bio-logging.
- AI Algorithms: Embedded into technologies, these can enable higher-throughput classification of images, sorting of identified 'particulates,' and navigation of vehicles to areas of highest biological interest. Similarly, data literacy and reporting using knowledge representation to enable broader use of machine learning tools.
- Further Digital Systems: These can include taxonomic annotation of species (i.e. cybertaxonomy, 3D imaging, microCT - remote taxonomic characterisation).

Marine Genetic Resources (MGR) will come under greater focus.

- New Resources and Biomimicry: Programmes to better explore the properties of marine biochemicals for use as pharmaceuticals, nutraceuticals, sustainable cosmeceuticals, as scientific tools, industrial chemicals such as enzymes and as inspiration for engineering and other applications.

There is a need for programmes to monitor habitat extent and condition.

- Habitat Mapping: Using remote sensing and *in-situ* observations to map the distribution and extent of critical habitats (e.g. seagrass meadows, coral reefs, kelp forests).
- Habitat Quality: Assessing the health and condition of habitats through indicators like water quality, substrate type, and presence of key species.

- Organism Health: Signs of disease or lack of reproduction (e.g. zombie populations, coral bleaching) are obvious signs of an ecosystem in decline.

5.5. General Description of Key Capabilities

5.5.1. People, Skills and Partnerships

A key component of the UK's future marine research infrastructure will be the development and expansion of the skills needed by the UK marine science community to respond to and support a large expansion in the volume of data being produced by new sensors and platforms. These need to be aligned with the UK's obligations under international treaties and with existing gaps in biological observations. Similarly, a multidisciplinary and quantitative understanding of marine ecology is required to continue to measure and understand changes, and to provide the knowledge frameworks to interpret impacts of projected change.

We recommend creating a hub (UK Marine Biodiversity [virtual] Centre) for measurement and (eventual) forecasting of marine life for a sustainable ocean. Recommendations for key components of such a hub would include:

- Collaborations with world-class UK organisations to provide cutting-edge technology, expertise, and resources necessary for cross-disciplinary projects focused on marine biodiversity. A Hub and Spoke could be developed that would divert (or have funded) elements of their programmes towards marine biodiversity assessment and forecasting, examples could include (but not limited to):
    - Wellcome Sanger Institute: A world-renowned genomics research centre with extensive expertise in sequencing and analysing genomes. They could work in parallel with a range of Genome Acquisition Laboratories (GALs) using a similar methodology to the Darwin Tree of Life Project (DToL).
    - National Centre for Coastal Autonomy (NCCA): A facility that delivers world-leading capability in use of autonomous vessels, sub-surface coastal platforms and scientific buoys, all integrated on a unique, high-speed marine communications network. Also extending collaborations to develop eDNA sensors for use in AUVs.
    - The Alan Turing Institute: The UKs national institute for data science and AI. By leveraging AI and ML, marine biodiversity researchers will gain deeper insights into marine ecosystems, improve monitoring and management practices, and enhance the effectiveness of conservation and forecasting efforts through development of more complex ecosystem / ocean system models and ocean digital twins.
- Other examples could include:
    - National museums and other biodiversity collections e.g. Culture Collection of Algae and Protozoa (CCAP).
    - Universities and other marine institutes with human capacity in marine taxonomy and biodiversity science.
    - International databases and facilities such as OBIS, other national institutions focussing on marine taxonomy.

5.5.2. Observational Infrastructure

As can be seen from the above there is a need to maintain, upgrade or develop technologies to study biodiversity for observations and sampling, *in-situ* to ex situ experimentation to long-term monitoring and mapping. For many parts of the ocean biodiversity is poorly studied and lack of knowledge is preventing evidence-based decision making on the sustainability of human activities such as deep-sea mining and marine carbon dioxide removal. Alongside these needs there have been years of investment and development of approaches for global observations of key EBVs (such as zooplankton and phytoplankton biodiversity), and EOVs which must be sustained for short to long-term monitoring of ocean biodiversity and health. The infrastructure requirements for marine biodiversity science are therefore complex, covering many scales of observation and sampling, using technologies from those developed in the 19th Century (e.g. bottom trawls and dredges) to leading edge technologies typical of the Fifth Industrial Revolution, including automation, robotics, AI, big data and virtualisation.

- We need to be able to collect physical samples from the ocean environment in order to increase knowledge of biodiversity and address open questions. This requires a range of capabilities from ship-based remote sampling using over-the-side sampling technology like cores and sleds to deep-submergence equipment. For coastal waters SCUBA divers or technical divers are still the method of choice for biodiversity sampling to depths of 100m.
- It is also crucial to maintain monitoring of ocean biodiversity but challenging to monitor changes and variability from periodic ship-based sampling.
- Global capacity will be maintained by satellites, but these can only see the surface. Autonomous assets are needed to bridge the gap between shipboard sampling and global satellite observations.
- Coordination with numerical and statistical models will be necessary to unify these disparate observing platforms/data sources (e.g. proxies for EOVs of interest when they can't be measured/observed directly).
- Global collaboration and coordination are needed to sustain global observations (e.g. BGC-Argo, MBON/OBON etc.).
- Science needs long-term funding sources and strategies encouraging collaboration, not competition, and needs to recognise the importance of data management and sharing infrastructure (which also needs funding) and repository coordination.

Assessment of Sustained Ocean Observing Programmes vs. Experimental Capacity from Research Platforms

It is critical that the UK maintains capacity to sample organisms (microbial communities to megafauna) and undertake experiments in the marine environment as well as sustained ocean-observing programmes (as reviewed by https://ocean-observations.uk/). Therefore, there will be a need for research platform capability (primarily research vessels) as well as new innovations in AUVs/ROVs and sensors to enable world-class capability in biodiversity and ecosystem health assessment and management.

Sustained ocean observing offers several key benefits for marine biodiversity assessments:

- Long-Term Data Collection for:
    - Trend analysis: Detecting long-term trends and patterns in biodiversity and indicators of ecosystem health and function.
    - Baseline establishment: Setting baseline conditions for future comparisons
    - *In-situ* validation for remote sensing.
    - Ensuring continuity of time series when sampling and/or data collection methods change.
- Comprehensive Coverage:
    - Spatial and temporal coverage: Ensures extensive data collection across various locations and times
    - Ecosystem representation: Includes diverse marine ecosystems, including remote ecosystems such as polar, open ocean and the deep sea.
- Enhanced Understanding of Ecosystem Dynamics:
    - Ecosystem interactions: Clarifies complex interactions within marine ecosystems
    - Response to environmental changes: Monitors biodiversity responses to changes like climate change and pollution.
- Support for Conservation and Management:
    - Informed decision-making: Provides data for effective conservation and sustainable management of human activities in the ocean including extraction of biotic and abiotic resources.
    - Effectiveness of conservation measures: Evaluates the success of measures like MPAs.
- Early Warning Systems:
    - Detection of anomalies: Identifies potential threats early, such as harmful algal blooms and invasive species.
    - Proactive management: Supports early mitigation efforts to prevent significant harm.

In parallel, research vessels can enhance experimental capacity by:

- Accessing remote areas: To enable exploration and sampling in remote (open ocean) and deep-sea environments which can't currently be accessed with remotely operated platforms alone.
- Use of advanced equipment: Research vessels are equipped with laboratories and specialised instruments for detailed analysis and mapping, as well as testing new innovations in sensors and samplers.
- Obtain functional biodiversity data: Through rate process and controlled incubation experiments.
- Explore specific biodiversity features in more detail: To gain more granular data for better understanding and future prediction on e.g. ocean fronts, gyres, upwellings.

- Ground Truthing Satellite Data: To ensure accuracy in remote sensing observing.
- Interdisciplinary Research: Foster collaboration among scientists from different fields.
- Real-Time Data: Allow immediate analysis and adaptive research responses.
- Education and Training: Provide field training and public engagement opportunities.

Recommendations for investment

- High priority: Global ship-based sampling capability; development of Hub & Spoke collaborative model for cross disciplinary engagement with world-class UK-based capability; advanced sampling and sensor development to support future autonomous innovations; mesopelagic AUVs; exploration of development of neutrally buoyant floating platform capability.
- Medium priority: (semi) Autonomous physical sampling capability. Expanded *in-situ* imagery of plankton and seafloor ecosystems (autonomous and ship).
- Lower priority: Hydrophones on autonomy and moorings?

5.5.3. Digital Infrastructure

Monitoring marine biodiversity requires a robust digital infrastructure that integrates various technologies and data sources. This integrated approach allows for comprehensive monitoring and management of marine biodiversity, supporting conservation efforts and sustainable use of marine resources. A summary of the key digital components include:

- Data Management and Sharing:
  - Important to address question of data management and FAIR data practices in order to make the best use of combined observations across platforms (e.g. *in-situ* data needed to validate satellite algorithms and models, as well as to train ML/AI models). This will likely require dedicated attention to data infrastructure with sufficient support for the effort needed.
  - FAIR data.
  - Submitting data to open repositories, e.g. Ocean Biodiversity Information System (OBIS), Marine Biodiversity Observation Network (MBON)...
- Remote Sensing Technologies:
  - Satellites: Used for large-scale monitoring of oceanographic parameters like sea surface temperature, chlorophyll concentration, and ocean colour, which are indicators of marine biodiversity.
  - Drones and autonomous Vehicles: These can capture high-resolution images and videos of marine habitats, providing detailed data on species distribution and habitat conditions.
- *In-situ* Sensors and Devices:

- Buoys and underwater sensors: Measure physical and chemical parameters such as temperature, salinity, pH, and dissolved oxygen levels, which are crucial for understanding marine ecosystems.
- Acoustic sensors: Used to monitor marine life, including tracking the movement of fish and marine mammals, and assessing underwater noise pollution. Seismo-acoustic studies can also be used to track marine mammals and other species.

- Molecular Techniques:
  - Environmental DNA (eDNA): Collects genetic material from seawater samples to identify species present in the area, providing a non-invasive method to monitor biodiversity (eventually including other biomolecules such as eRNA, eProteins, and eMetabolites).
  - Genomic data: Helps in documenting genomic diversity and to populate databases with genes from specific organisms to help understand biodiversity and evolutionary dynamics.
- Data Integration and Analysis Platforms:
  - AI and machine learning: These technologies process and analyse large datasets from various sources, identifying patterns and predicting changes in biodiversity.
  - Interactive Dashboards: Visualise data for policymakers, researchers, and the public, facilitating informed decision-making and conservation efforts.
- Communication Networks:
  - Low-power radio networks: Enable real-time data transmission from remote sensors to central databases.
  - Internet of Things (IoT): Connects various monitoring devices, ensuring seamless data collection and integration.

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Chapter 6: Marine Pollution: Its Sources, Distribution and Solutions

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6.1. Scope and Context

Marine Pollution can be defined as 'direct or indirect introduction by humans of substances or energy into the marine environment, resulting in harm to living resources, hazards to human health, hindrances to marine activities, impairment of the quality of seawater and reduction of amenities' (European Environment Agency definition) and is a global societal and environmental concern and adversely affects marine resilience, ecosystem services and human health. Pollution is one of the three main, interlinked issues that humanity currently faces (together with climate change and biodiversity loss), referred to as the triple planetary crisis. Each of these three issues need to be resolved if we are to have a viable future on this planet. From a scientific perspective, to effectively explore the causes, scope and impact of marine pollution, a combination of advanced technologies and methodologies are essential. These include remote sensing, *in-situ* sensors, laboratory experimentation capabilities and analyses, modelling, data integration, artificial intelligence support, and environmental engineering. Together, these provide a more comprehensive understanding of the fate and behaviour of current effects, and the behaviour of future effects, of marine pollution in the ecosystems. This understanding enhances detection and prediction, supports effective monitoring, risk assessment, source apportionment and remediation, and informs innovative management of human activities that cause marine pollution and policy strategy to protect marine environments.

The marine pollution crisis is a product of multiple interlinked anthropogenic activities, including economic growth, industrialisation and unsustainable consumerism. Key contributors span agriculture, manufacturing, shipping, and resource extraction. These industries release a wide range of pollutants into the marine environment both directly and indirectly (through runoff/discharge into rivers and drainage systems), such as plastics (and microplastics), heavy metals, excess nutrients (from fertilisers), hydrocarbons, and wastewater. In many coastal regions, rapid infrastructure development but limited waste management processes and weak regulatory support amplify the issue. To develop an effective requirements framework for addressing marine pollution, it is crucial to establish an integrative coastal management framework with land-sea coordination (as >80% pollutants originate from land), implement educational and public awareness campaigns, promote sustainable human practices, and engage with national and global initiatives. International programs and initiatives focused on marine pollution are often collaborative efforts involving multiple countries, organizations, and stakeholders, aimed at strengthening scientific research and monitoring, and improving data sharing and collaboration.

An example of an international initiative is the Back to Blue (an initiative of Economist Impact and The Nippon Foundation) who published 'A global ocean free from the harmful impacts of pollution: Roadmap for action', in March 2024 at the World Ocean Summit. The roadmap is a strategic framework to build a comprehensive evidence base to tackle ocean pollution collectively. Now, IOC-UNESCO and UN Environment Programme (UNEP) propose a new UN Ocean Decade Programme entitled 'A Global Ocean Free from the Harmful Impacts of Pollution by 2050'. The Ocean Decade also published the 10 Vision 2030 White Papers, each focusing on a specific Ocean Decade Challenge, representing a collaborative effort to develop the science we need for the ocean we want, and the planet needs, by 2030. The White Paper on 'Challenge 1: Understand and Beat Marine Pollution' which provides a pivotal blueprint for understanding and mapping land- and sea-based sources of pollutants and contaminants, and their potential impacts on human health and ocean ecosystems, and for developing solutions to remove or mitigate them. Key international cooperation is provided via the Regional Sea Conventions (RSCs) which require contracting parties to undertake monitoring, and many sit under UNEP. The execution of monitoring requirements is carefully observed with regular reporting procedures. RSC guidance drives many of the existing monitoring efforts in the UK, covering hazardous substances, noise, nutrients, and biodiversity, to name a few.

The UK Marine Strategy is focused on a vision for 'clean, healthy, safe, productive and biologically diverse oceans and seas' and aims to combat marine pollution. The regulations within it set out a framework repeating every six years, requiring the UK to assess the state of its seas, define environmental targets (to achieve Good Environmental Status [GES]), implement monitoring programmes, and establish a programme of measures to meet those targets. It covers 11 descriptors of marine health, including biodiversity, contaminants, litter, and underwater noise. The Strategy coordinates efforts across government divisions, devolved administrations and with those that share seas with the UK.

By 2040, scientific developments and technological advancements are expected to play a crucial role in further enhancing our understanding of the consequences of marine pollution (UN SDG14; Regional Sea Convention Quality Status Reports), enhancing our understanding of our capacity for, the timeline on and thresholds for restoring marine ecosystems, providing evidence to ensure the sustainable use of ocean resources and reduction of marine pollution events. Knowledge of the scope and scale of marine pollution is fragmented, and understanding of the impact of marine pollution on species and ecosystems is far poorer still. Whether ecosystems can meaningfully be restored and what assessment criteria are appropriate is a question that future research will need to address. In this frame, the scope of the Marine Pollution Grand Challenge is to support coordinated, collaborative, and collective efforts to develop an economically and environmentally sustainable approach to research infrastructure and long-term monitoring programmes for current and future marine pollution research and monitoring, within the context of the other Grand Challenges and the wider UKRI research environment.

6.2. Anticipated Scientific Developments by 2040

Best Available Techniques (BAT) and Best Environmental Practice (BEP) followed in all facilities to ensure reproducibility, accuracy, and precision and reduce methodological bias. This will produce data of a known quality that can be used in models, enhance understanding of the problem through comparison with internationally agreed assessment criteria (e.g. OSPAR Background Assessment Concentrations), and better inform policy and decision making around human activities which cause marine pollution. There are BATs and BETs are available, but they do not encompass all types of pollution. However, there is a need to review what exists and what needs developed with the resulting new 'products' being stored in a public repository, e.g. Ocean Best Practices System (OBPS) which was formally adopted as an IOC Project in June 2019, joint sponsored by the IODE and GOOS Programmes. BPs will be agreed by a community of experts, will be available for continuous community review, and will include ISO recommendations. To be used in regulatory programmes and form part of the determination of GES, BPs will have to be agreed by the UK's governments, Administrations and the organisations undertaking the monitoring.

Unified Certified Reference Materials (CRMs) to be used in all UK facilities and coordinate with other international initiatives. Facilities will need to report on values from these materials. Some CRMs are commercially available but for some pollutants or groups of them, laboratories need to prepare their own in-house reference materials. UK experts will have to agree on protocols to produce these CRMs and intercalibration exercises will also be required. Experts will engage with metrology institutions and national institutes of standards among others to ensure traceability of the material and to secure its production in the future. For those pollutants where processes are already in place, it will be key to build on existing practices – for example, the international quality assurance programme QUASIMEME.

Enhanced long-term monitoring infrastructure and strategy. This will include long-term ocean monitoring sentinel stations as recommended in the Ocean Decade Vision 2030 White Papers. These stations will include historical and new stations. Data collected will provide data on trends, identify hotspots and pollutants of concern, and support the development of effective control and mitigation strategies which will deliver on the aim of achieving near background levels for naturally occurring substances and near zero levels for man-made synthetic substances in the marine environment.

Ability to deal with complex, high frequency data that provides clear outcomes to the needs of long-term monitoring and assessment programs. Currently, the majority of the data collected through autonomous or high frequency (big data) means are not fit for purpose in monitoring and assessment programs because they lack the necessary standardisation, calibration and metadata required for use. Artificial intelligence (AI) and machine learning (ML) may provide some of the solutions, but we need to reconsider current monitoring indicators and how policy tracks environmental changes. Big data will not always provide the critical nuances needed to guide policy, so this requires both bottom-up and top-down rethinking on monitoring frameworks, applicable national and international environmental indicators, and adequate use of big data with AI and ML to resolve questions, or (at least) add to our understanding of annual and multi-annual changes. **This will also require consideration of the current unified datasets portal with all available measurements and harmonization and how this needs to be developed.**

UK archives to store samples for sharing and future studies. This will also require harmonization and standardisation of sampling methods and storing requirements etc., using, where possible, already operationalised process and procedures to ensure continuity of time-series. Having BPs in place for sample collection and preservation, where they do not already exist, will help to fill all requirements. More detail on this is covered in the Clean Seas Environment Monitoring Programme (CSEMP). Emerging pollutants are being discovered every day, and their effects are, in most cases, still unknown. Therefore, collecting and storing high quality samples in centralised specimen bank(s), will help to address future challenges, providing the opportunity to access and investigate historical samples. This will need to be taken into account when defining the BPs.

UK database around labs/institutions/companies to increase visibility and collaboration. Efforts from interested parties will be required to keep this database up to date. This can build on existing efforts such as UKDMOS (http://www.ukdmos.org/) and MEDIN (https://medin.org.uk/).

Efficient sample collection strategy. Engaging with other scientific areas to collect samples in a more efficient way: reducing time on board ships by lowering the manpower required to take samples with autosamplers and robotics, and increasing the number of samples collected per unit time, e.g. using random stratified sampling. Onboard technicians and researchers will follow BP protocols for sample collection and preservation. This might require a managed database for better coordinating scientists to engage with planned activities they can join and to publicise any activity that can include extra sampling.

6.3. Key Science Questions, Knowledge Gaps and Uncertainties

In the Back to Blue report, four gaps were identified: (1) the scale gap, scientists have local knowledge but are unable to draw conclusions about wider ocean ecosystems; (2) the FAIRness gaps, datasets fail to adhere to the FAIR principles: Findability, Accessibility, Interoperability and Reuse of digital assets; (3) the geography gap – we know a lot about some parts of the ocean, and almost nothing about others; (4) the long-term monitoring gap, point-in-time studies make it difficult to discern trends. The list of pollutants suggested in the B2B Roadmap was used as a starting point. Experts agreed on the list, but some new groups were also recommended (see Table 6.1). Below is a summarised list of key science questions, knowledge gaps and uncertainties.

Identify thresholds of toxicity/ecological impact within a multi-stressor system: Addressing marine pollution requires a holistic approach that considers the interconnectedness of pollutants with other Grand Challenges and their combined effects on marine ecosystems. Understanding the interactions of pollutants with other environmental stressors such as physical changes (habitat destruction, temperature shifts, anthropogenically driven change in pH), or biological factors (invasive species, diseases) is crucial, as is understanding the additive, synergistic, antagonistic, or potentiation effects of mixtures of pollutants and stressors (Piggott, Townsend and Matthaei, 2015). To **incorporate the consideration of** the impact of pollutants within an environmental and climatic change context, it means that effect thresholds **could** be reached even if individual pollutants are below their harmful levels.

Identify long-term effects, including on resilience and transgenerational effects: Many chemical pollutants persist, leading to bioaccumulation and biomagnification in the marine environment. They can also undergo (bio)transformation processes. Pollutants may not only affect the exposed individuals but might also have consequences for subsequent generations (i.e., affecting mechanisms such as genetic, epigenetic, and developmental pathways) resulting in long-term (and potentially irreversible) ecological impacts. Recovery of individual organisms and ecosystems after pollution cessation or mitigation intervention should be revealed and such information of ecosystem resilience will be essential to management of expectation and development of strategy.

Assess hotspots of ecological risk as well as human and societal risk: It is important to identify specific marine areas characterized by high levels of biodiversity, significant ecological functions, and intense human activities that pose risks to marine health. These areas could be particularly sensitive to specific types of pollution.

Estimate pollutant pathways and fate to assess states and trends: Understanding how pollutants enter, traverse, and persist in the marine environment is fundamental to managing the associated human activities for beating marine pollution. This process includes identifying sources, transport mechanisms, chemical transformations (when relevant), and ultimate sinks or destinations of pollutants.

Identify a common criteria-based approach to understand the impacts of marine pollution and how to tackle the problem: Due to the vastity of pollutants, especially when including energy entering into and propagating through the marine environment, it will be crucial to further develop BAT and BEP methodologies to understand the overall impact of a pollutant and the impact of pollution as it is rare for any sea area to experience only a single pollutant. In this regard, the first step will be to deliver as simple an overall method as possible. As an example, one could first identify the functional typology of pollutants (i.e., bioaccumulation, biomagnification, toxicology), secondly, select a marker of general pollution as a proxy of occurrence and frequency, and finally, identify the main driving vectors (biological, chemical, physical) for spatiotemporal variations of the marker level. In doing this, current procedures and protocols must be reviewed as these are the protocols that have resulted in the current assessments at local, national and international levels.

Evaluate the efficacy of measures to address pollution: Without long-term monitoring data, the efficacy of local to international scale interventions to address pollution cannot be adequately evaluated. International cross-sectoral collaboration, laboratory infrastructure and access to historical data and samples are therefore a necessity in tackling pollution. Sharing databases and/or establishing open access databases will be essential for addressing marine pollution as oceans have no boundaries. In some countries, processes are well developed, however, even in these countries there is a need to ensure that the full suite of pollutants to which biota are being exposed are included in the assessments, using a risk-based approach. In other words, there is a need to identify the pollutants causing the greatest ecological impact in an area.

6.4. Observation and Product Requirements

6.4.1. Observation

Scaling up from organism to population and ecosystem: This is fundamental to achieve a comprehensive and holistic understanding of pollution impacts (including, for example, habitat alteration and trophic interaction), leading to more effective environmental management and conservation strategies. This is, however, extremely challenging and will require a concerted effort.

Large-scale and temporal data coverage: Robust datasets are fundamental for addressing the complex and evolving challenges posed by marine pollution. They enable the detection of long-term trends and seasonal variation, to assess the level of chronic exposure as well as acute events (i.e., chemical spills), synergistic impacts and the prediction of future scenarios.

Policymakers rely on robust data to create effective regulations to control pollution levels and mitigate risks. Additionally, scientifically based assessment criteria shall be developed.

6.4.2. Products

Enhance data availability and statistical analysis to validate modelling: A lot can be done looking at and combining historical data. This will involve building on existing infrastructure to establish a centralized database or repository and foster national data-sharing agreements, as well as enhancing computational infrastructure to support the processing and analysis of large datasets, and investment in developing advanced sensors for real-time monitoring of a wide range of pollutants, covering wide coastal and seascape regions.

Standardize measurements/best practices for dataset inter-comparability. This should include the developing of protocols ('Cookbook' concept, i.e., a publicly available repository for community agreed methods and reviewed by a community of experts) which allow users to find values for uncertainty, precision, accuracy, etc within different laboratories and methods. In future, all government funded marine pollution or environmental quality related projects in the country must deposit relevant environmental monitoring data into the centralised environmental database following a standardised format. Such a centralised environmental database will be highly useful for tracking the spatiotemporal change of environmental quality, and for environmental impact assessment of future large-scale developmental coastal and marine projects.

6.5. General Description of Key Capabilities

6.5.1. Digital Infrastructure

Increase model and statistical capability. These capabilities can be leveraged using big data analytics including integrated, diverse data sources; predictive models, including hydrodynamic modelling, such as pollution dispersion and ecosystem impact models; and statistical risk models and/or Probabilistic Risk Assessment (PRA) to assess the probability and potential impact of pollution events, and to formulate control strategies. Atmospheric models, sound propagation models, riverine discharges (especially for nutrients) are also needed.

Develop AI and observation from space for rapid/large area surveys. Machine learning algorithms, particularly Convolutional Neural Networks (CNNs), can analyse satellite images (and drones equipped with a high-resolution camera) to detect oil spills, plastic waste, and other pollutants (e.g., anthropogenic nutrient induced algal blooms) in the ocean. AI-powered geospatial analysis tools can create maps of pollution distribution, helping to identify pollution sources.

6.5.2. Observational Infrastructure

Improve and increase availability of equipment and technology for *in-situ* sampling and analyses for revealing multi-stressor impacts of combinations of contaminants. This should include multi-stressor and long-term experimental facilities, statistic and dynamic marine platforms, and low-power, high-sensitivity autonomous sensors and samplers (i.e., chemical sensors, biosensors, AUVs and ROVs, diffusive passive sampling device such as Gradients in Thin films (DGT) or Semipermeable Membrane Devices (SPMDs), active samplers and Lab-on-a-Chip (LOC) Devices). Biological responses to pollution and multiple stressors can be revealed by environmental DNA (eDNA) based biodiversity information and expression of DNA and RNA in individual bio-monitor organisms based on the Adverse Outcome Pathways.

Creating and evaluating advanced waste treatment. This also includes recycling technologies and innovative methods for cleaning up existing marine pollution.

6.5.3. People, Skills and Partnerships

Education and awareness raising. This includes opportunities for cooperative and intersectional analytical and social science solutions, such as the use of citizen science to increase sample collection and data generation, while increasing awareness. Although some citizen science initiatives will be hampered by pollutants requiring specific and complex sample collection methods (e.g. those that require the avoidance of plastics).

Engage more positively with industry and other stakeholders. Scientists and industry can collaborate on R&D projects (to develop new technologies and methods for pollution control, waste management, and sustainable production processes) and establish industry-scientist advisory panels to provide guidance on pollution reduction strategies. Industries should be mandated to make environmental data publicly available, allowing scientists to analyse and provide insights for improvement and collaborate to promote policies and regulations that support sustainable industrial practices and pollution reduction. Engagement with the financial services sector is essential, given its influential role in shaping investment decisions and, consequently, the behaviour of industry and business. Financial institutions (Fis) are gradually being integrated into emerging climate- and nature-related risk and transparency frameworks, such as the Task Force on Climate-related Financial Disclosures (TCFD), the Taskforce on Nature-related Financial Disclosures (TNFD), and Science-Based Targets (SBTs). However, pollution has not yet been substantially incorporated into these frameworks; though, it is expected to gain prominence over time. Due to the complex and multifaceted nature of pollution, financial institutions often face significant challenges in determining which data are relevant for investment and capital allocation decisions. In this context, scientific expertise will play a crucial advisory role in guiding the development and implementation of effective and credible pollution-related disclosure and assessment frameworks.

Foster collaborations and knowledge sharing. Effective communication and knowledge exchange between facilities and disciplines are essential to reduce competition for funding, maintain the broad capability of the scientific community and synergise efforts. This will support interdisciplinary scientific field studies and collaborations.

Increasing dialogue around management strategy to prevent, mitigate, reduce, and regulate. This will require an integrated approach that combines regulatory frameworks, technological advancements, industry best practices, and community engagement.

6.6. References

Piggott, J.J., Townsend, C.R. and Matthaei, C.D. (2015) ‘Reconceptualizing synergism and antagonism among multiple stressors’, *Ecology and Evolution*, 5(7), pp. 1538–1547. Available at: https://doi.org/10.1002/ece3.1465.

6.7. Annex

6.7.1. Global Initiatives

Relevant global initiatives were identified:

- Ocean Decade, United Nations has 10 Challenges. A few months ago, 10 White papers were released, and 1 was specific for Pollution: Challenge 1: Understand and beat marine pollution
- Back to Blue includes several initiatives for pollutants.
- World Health Organization (WHO) policy brief.
- UK 5-year action plan for AMR
- EU Marine Strategy Framework Directive (MSFD)
- Water Framework Directive (WFD) England and Wales
- Nutrient Pollution – Global Action Network (NP-GAN)
- Harmful Algae Bloom Solutions (HAB-S) Programme
- Intergovernmental Negotiating Committee on Plastic Pollution
- OSPAR
- MERMAN is a national database which holds and provides access to data collected under the Clean Safe Seas Environmental Monitoring Programme (CSEMP) – formerly the National Marine Monitoring Programme (NMMP).
- QUASIMEME catalogue covers various programmes of contaminants in seawater, biota and marine sediment.
- Offshore Chemical Notification Scheme (OCNS) applies to chemicals that are intended for use and discharge in the exploration, exploitation and associated offshore processing of petroleum in the UK and Netherlands.
- Marine Natural Capital and Ecosystem Assessment Programme (mNCEA) is Defra's flagship 3-year research and development programme that will provide a robust evidence base, suite of tools and a framework where ecological, societal, and economic information is brought together in a holistic way.
- The Global Estuaries Monitoring (GEM) Programme is an UN endorsed Ocean Decade Programme to develop a global sampling network to monitor contaminants of emerging concern (e.g., pharmaceuticals) using standardised sampling and analytical methods.

6.7.2. List of Pollutants Identified

The list of pollutants suggested in the B2B Roadmap was used as a starting point. Experts agreed on the list, but some new groups were also recommended (see Table 6.1).

Table 6.1: Groups of pollutants to include.

Group of Pollutants	**Comments**	**Phenomena to Capture, Scales of the Phenomena**	**Current Observing Networks, Maturity and Scale**	**Future Observing Capacity**
BACK TO BLUE ROADMAP				
Persistent bio-accumulating and toxic compounds (PBTs)	Those that accumulate in the environment and remain persistent over long periods. This includes persistent organic pollutants (POPs), per- and polyfluoroalkyl substances (PFAS), and some pesticides.	Main processes: bioavailability, bioaccumulation (biomagnification), biological role and toxicity of PBTs: - Effect of route of transport on PBT bioavailability. - Factors affecting the bioaccumulation of PBTs - Toxicity of PBTs. - Assessment of PBTs toxicity and bioavailability from polluted marine sediments.	- Discrete samples: water, air, biota, sediments (and sediment cores for historic vs contemporary inputs) from local (monitoring programmes) to global coverage (e.g. Caribbean Coastal Pollution Project (CCPP) to study POPs in mammals and ecological and human influence). - UK Marine Strategy for sediments[2], water and biota: following OSPAR Convention and Water Framework Directive (WFD).	- Autonomous platforms equipped with *in-situ* sensors/samplers. - Ecotoxicology infrastructures. - *In-situ* incubators for sediment-water interactions. - *In-situ* samplers/sensors for sediment samples.

[2] https://moat.cefas.co.uk/pressures-from-human-activities/contaminants/

		- Biological role of PBTs and human health hazards. - Cumulative impact with other pollutants.		
Potentially Toxic Elements (PTE)	Heavy metals (Including mercury, lead, copper and cadmium) and metalloids such as arsenic.	Enter the marine environment from a number of natural, agricultural, and industrial processes, via long-range transport by air, riverine input, or run-off from land. Main processes: bioavailability, bioaccumulation, biological role and toxicity of heavy metals: - Effect of route of transport on metal bioavailability. - Factors affecting the bioaccumulation of heavy metals. - Toxicity of heavy metals. - Assessment of heavy metal toxicity and bioavailability from	- Discrete samples: water, air, biota, sediments (and sediment cores for historic vs contemporary inputs) from local (monitoring programmes) to global coverage (e.g. GEOTRACES). - UK Marine Strategy for sediments, water and biota: following OSPAR Convention and Water Framework Directive (WFD). Marine Strategy Framework Directive Good Environmental Status, UK Marine Strategy Good Environmental Status. - Multidisciplinary research projects air-sea interactions (SOLAS).	- Autonomous platforms equipped with *in-situ* sensors/samplers. - Ecotoxicology infrastructures - *In-situ* incubators for sediment-sea interactions. - *In-situ* samplers/sensors for sediment samples.

		polluted marine sediments. - Biological role of heavy metals and human health hazards. - Cumulative impact with other pollutants.		
Nutrients	E.g. from fertilisers and organic matter, including human and animal waste. Can lead to eutrophication, where algal blooms consume so much oxygen from the water that other sea life dies.	GOOS Essential Ocean Variables (EOVs): - Ventilation; annual to decadal; 1000-3000 km. - Primary production; seasonal to decadal; Coastal (0.1-100 km), Open-ocean (100-1000 km). - Eutrophication; sub-weekly to decadal; Coastal (0.1-100 km).	GOOS EOV: - Ship-based underway observations; Pilot; Horizontal coverage (surface); weekly to decadal. - Ship-based repeat hydrography; mature; Horizontal and vertical cover; decadal. - Ship-based Fixed-point observatories; Mature; Horizontal cover (local); weekly to decadal. - Profiling floats; pilot; Horizontal cover (Global). - Profiling floats; Pilot; Horizontal cover (global).	GOOS EOV: - Underwater and surface vehicles. - Moored fixed-points observations.

Plastics	Including plastic products, plastic material, the polymers, intentionally and unintentionally added substances in plastic materials, nano- and microplastics and other degradation and breakdown products, and other chemical emissions related to industrial processes throughout the plastic lifecycle from extraction, through production, use and waste.	- Ecotoxicological impact of plastic in future multi-stress marine environment (including cumulative impacts with other pollutants) under short- and long-term exposure. - Identify behaviours and fate of plastics exposed to environmental change/weathering. - Vertical residence time of plastics, from sea-surface to seabed. - Increase the number of plastic pollutant monitoring sites globally. - Monitor the transfer of plastics (and their associated chemicals) through the marine food web and assess potential impacts on human health. - Assess land-sea flows of plastics, and assessments of known point-sources e.g. sewage effluent.	- At the global scale, GOOS, under the Intergovernmental Oceanographic Commission (IOC) of UNESCO, is working to include marine plastic pollution as an Essential Ocean Variable (EOV). This is still in development, but it aims to standardize methods for data collection and provide a coordinated approach to global plastic monitoring (GPML). It is led by the United Nations Environment Programme (UNEP) and is a voluntary partnership. - The Ocean Conservancy International Coastal Cleanup (ICC) is the world's largest volunteer effort to collect and document marine litter, including plastics, from coastlines. Regional scales are covered by	- Controlled multi-stress mesocosm platforms. - *In-situ* oceanic plastic degradation/behaviour platform (Moored and drifting float). - Globally accessible plastic polymer spectral library. - Enhance the use of AI and machine learning algorithms for the automated detection, classification, and quantification of plastic pollution from imagery and sensor data. - Underwater vehicles (AUVs), drones, and gliders equipped with sensors and cameras to conduct large-scale and fine-scale surveys of marine plastic. - *In-situ* sensors and smart buoy to monitoring in continuous micro and nano plastic presence. - Establish global standards and protocols for marine plastic monitoring, including sampling methods, data processing, and reporting.

			bodies such as NOAA and OSPAR, through the Contracting Parties and provide continuous monitoring.	
Pharmaceuticals	Including medications for humans and animals, with antibiotics a central concern given their overuse or misuse.	- Sources: Sewage effluent, aquaculture, animal husbandry and horticulture, waste disposal. - Processes[3]: pharmaceuticals and their metabolites can undergo biotic and abiotic transformation (degradation) and sorb to suspended particulate matter (SPM) and sediments, and in some cases accumulate in the tissues of aquatic organisms. This will be affected by physicochemical	- Discrete samples: water, biota, sediments. - Sewage discharge legislation: Annex IV of MARPOL 73/78 ships. - Water Framework Directive[4] (WFD; Directive 2000/60/EC) covers both freshwaters and transitional waters (the estuarine and coastal area up to one nautical mile, or 1.85 km, from the shore). Two hormones (17α-ethinyloestradiol and 17β-oestradiol) and diclofenac have been placed on a watch list for	- Improve monitoring of dissolved and particulate fraction of relevant pharmaceuticals and degradation products. - Improve data for the accumulation of other classes of pharmaceuticals, their metabolites and transformation products in marine organisms - Improve geographic / seasonal, coverage data

[3] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4213585/
[4] https://www.legislation.gov.uk/uksi/2017/407/contents

		conditions of the environment. - Antimicrobial resistance. - Seasonal trends, sediment concentration, marine ecotoxicology, factors influencing concentration.	emerging pollutants under the WFD.	
Radioactivity	Including recent contamination, the historical dumping of radioactive waste, licensed and other discharges from nuclear facilities, and radiation from natural sources.	Nuclear waste comes from a variety of sources, such as nuclear power plants, nuclear waste recycling plants, nuclear-powered vessels and weapons testing, offshore industrial activities, hospitals, scientific research centres, and nuclear weapons facilities, as well as from events such as nuclear spills, the sinking of a nuclear-powered submarine, or leakage from sealed waste. There is also natural radiation. Processes: - Effects of nuclear waste on marine biota: genetic	- Discrete samples of biota, water and sediments (and sediment cores for historic vs contemporary inputs): UK organisations carry out monitoring programmes to provide an independent assessment of radiation levels in the environment. (UK strategy for radioactive discharges: 2018 review of the 2009 strategy). - OSPAR Recommendation 2018/01 on Radioactive	- Measurement of radioactivity in the environment - more accurate and rapid radiometric methods (including *in-situ* methods). - Potentially nuclear fusion could place a renewed emphasis on tritium. Given concerns about tritium releases from Fukushima and a new focus on tritium releases from nuclear sites worldwide, tritium may become of more interest, though of course it is currently routinely measured as part of site environmental programmes. - More emphasis on elements or analogues for environmental mobility of very long-lived elements in nuclear waste. More emphasis on naturally occurring radioactive

		mutations, development or reproductive changes, cancer, decreased lifespan, and death. - Transport, fate and impact. - Dose to critical groups (e.g., through the discharge of radioactive waste from reprocessing plants into the marine environment, i.e., Sellafield, UK). - Existing baselines (against which to benchmark potential future inputs from waste storage and disposal).	Discharges[5] and North-East Atlantic Environment Strategy (NEAES) 2030[6].	materials (NORM) waste. There is significant historical and ongoing NORM waste from e.g. oil and gas extraction. - Model developments: this is a mature field and there has already been a lot of model development and process understanding. More importance should be given to application and testing of models. Continuing work on models for nuclear waste disposal and long-lived radionuclide migration, particularly if a UK waste disposal site is chosen. - Ecotoxicology/radioecology: there has been and will be a lot of work on environmental impacts of radioactive pollution. Most of this work is not properly hypothesis driven nor are the current very vague hypotheses properly tested. Progress in this is likely to be limited unless key issues (lack of testable hypotheses, lack of attempts to reproduce findings,

[5] https://www.ospar.org/documents?d=38954
[6] https://www.ospar.org/documents?v=46337

				problems with determining if radiation is the causal factor in apparent effects seen in the environment) are properly addressed. - Modelling capabilities are important: these need to be informed by *in-situ* observation. Statistical capability is important. - Models have been developed for regulation of routine discharges, for accident scenarios and for geological disposal of nuclear waste. Ongoing work is needed to ensure these are robust and that there is sufficient capability for future needs. Time scales range up to say 100,000 years for geological waste disposal.
Oil	Including the toxic chemicals (dispersants) used to clean up spills.	Oil spills. Main sources are shipping, port and harbours, and offshore oil and gas industries	- Discrete samples: water, air, biota, sediments. From local (monitoring programmes) to global coverage (e.g. Caribbean Coastal Pollution Project (CCPP) to study POPs in	- For satellite: Need for a valid database with spills and lookalikes for algorithms improvement; new “multi or hyper” band radar sensors to eliminate the detection errors; AI to process large amount of data (Topouzelis, and Singha, 2016).

			mammals and it's ecological and human's influence) - UK Marine strategy for sediments, water and biota: following OSPAR Convention and Water Framework directive (WFD). - Sensors installed in moorings, mobile platforms and satellites. - UK has a well-developed and exercised process of response, including measures set out in the UK National Contingency Plan. UK Government is fully engaged with European and international partners across a range of groups and initiatives relating to the prevention of spills including those presided over by OSPAR, International Maritime	- New type of *in-situ* measurements: low-cost buoys with sensors measuring the type of oil and its chemical composition; small AUV/UAVs for large area monitoring in high resolution.

			Organization[7] and European Maritime Safety Agency[8].	
Household and consumer chemicals *The list of chemicals in the average home is long, featuring items like solvents and household cleaners, mould removers, laundry products, detergents, bleach, furniture polish, air fresheners, paints and varnishes, poisons (insecticides, for example) and batteries.*	Many cleaning products contain toxic chemicals, as do numerous cosmetics (Benzophenone[9]), shower gels and sunscreens.	Many cosmetics, shower gels, deodorants, shampoo and sunscreens, for example, contain benzophenone or its derivatives oxybenzone130 and dioxybenzone,131 which are used for their ability to absorb UV-A and UV-B light. Oxybenzone is toxic to aquatic life and has long-lasting effects, as are other substances added to some sunscreens such as octinoxate, 4-methylbenzylidene camphor and butylparaben.	- Discrete samples for some research studies. - Some components are banned, like Benzophenone in cosmetic products.	We need more studies to understand: - The impact of these products in marine life. - To fill major data gaps regarding the trends of emerging contaminants in freshwater and marine environments as well as their impact on aquatic wildlife in the UK. - Understand the impact when they are combined with many other stressors such as climate change and habitat loss.
Pseudo-persistent chemicals	These would dissipate relatively quickly in the aquatic environment,	Main processes: bioavailability, bioaccumulation	- Discrete samples: water, air, biota, sediments. From local	More research[10] is needed to determine how long chemicals persist in the environment versus

[7] http://www.imo.org/en/About/Pages/Default.aspx
[8] http://www.emsa.europa.eu/
[9] https://www.legislation.gov.uk/eur/2009/1223/annex/II
[10] https://backtoblueinitiative.com/wp-content/uploads/2022/11/Chemical-pollutants-of-major-concern.pdf

For UNEP, a half-life longer than 60 *days in water falls into the persistent category.* *Stockholm Convention and other* *regulatory lists of hazardous chemicals.*	except that their concentrations keep rising because they are so prevalent in products. Some examples of which include anti-inflammatory drugs, UV filters in suncreams, and artificial sweeteners.	(biomagnification), biological role and toxicity: - Effect of route of transport on chemicals bioavailability. - Factors affecting the bioaccumulation of chemicals. - Toxicity. - Assessment of chemicals toxicity and bioavailability from polluted marine sediments. - Biological role of chemicals and human health hazards. - Cumulative impact with other pollutants.	(monitoring programmes) to global coverage.	their persistence in a laboratory setting, not least as persistence is one of the key criteria for inclusion in the Stockholm Convention and other regulatory lists of hazardous chemicals.
Other chemicals	Including a wide variety of the approximately 300,000 chemicals in use, most of whose effects on the environment and human health are unknown.	Main processes: bioavailability, bioaccumulation (biomagnification), biological role and toxicity: - Effect of route of transport on chemicals bioavailability.	- Discrete samples: water, air, biota, sediments. From local (monitoring programmes) to global coverage.	- Autonomous platforms equipped with *in-situ* sensors/samplers. - Ecotoxicology infrastructures. - *In-situ* incubators for sediment-sea interactions.

		- Factors affecting the bioaccumulation of chemicals. - Toxicity. - Assessment of chemicals toxicity and bioavailability from polluted marine sediments. - Biological role of chemicals and human health hazards. - Cumulative impact with other pollutants.		- *In-situ* samplers/sensors for sediment samples. - Needs more sample screening to detect new components. - Store samples for future experiments.
INPUT FROM MEETINGS				
Invasive non-native species (INNS)	Including species that can alter marine ecosystems.	- Identify source, Population Growth and Spread. - Ecological Impact (short term versus long term) which includes Displacement of Native, Species, Genetic Pollution and Habitat Modification.	- Global Ballast Water Information Clearinghouse (GBWIC) is an established network within the International Maritime Organization (IMO) and the Global Invasive Species Programme (GISP). It was developed to monitor and manage the spread	- Remote Sensing and Satellite Technology with High-Resolution Imagery and Spectral Sensing Monitoring large-scale marine habitats and coastal zones for signs of invasive species and tracking the movement and spread of invasive species in real time. - Environmental DNA (eDNA) Technology including High-Sensitivity Detection: of low

			of invasive species through ballast water. - Global Invasive Species Database (GISD) has a Section managed by the IUCN's Invasive Species Specialist Group (ISSG). - Alien Species Information Network (EASIN) is an integrated system within Europe, created by the European Commission. This network has a marine component that focus on monitoring invasive species in European marine environments. - The Marine Aliens Project, supported by the UK government and various academic institutions, is a mature network focused on monitoring marine invasive species in the United Kingdom. Covers UK coastal and marine environments. Involves	concentrations and use of Portable Devices for field-based testing and faster results. - Artificial Intelligence (AI) and Machine Learning for the prediction of invasive species spread and Automated Image Analysis of remote sensing imagery and underwater videos/photos. - Real-Time-Rapid Response Systems-sensors.

			both historical analysis and continuous monitoring.	
Noise	Ocean sound, including underwater noise pollution.	- Enhancing ability to track and manage marine noise pollution on various scales. - Continuous Underwater Noise generated in the ocean from shipping traffic or other offshore activity and Short, high-intensity noise events that occur sporadically such as underwater explosions, pile driving. - Impact on marine life and behaviour of different types of Noise i.e. vibratory versus tonal noise and/or any Noise that directly interferes with the sounds produced by marine organisms.	- Noise impacts on specific species, such as whales using arrays of hydrophones and classification of sound sources, including both natural and anthropogenic noise. - Standardized methods and protocols for global data collection. - Global Networks include International Quiet Ocean Experiment and Ocean Sound EOV. Same Regional networks operate continuously, with fixed hydrophone arrays (IOOS [US], ONC [Canada]), OSPAR Thematic Assessment on Underwater Noise.	- Real-time data collection and AI-driven analysis. Implement satellite-linked buoys equipped with hydrophones. - Utilize Internet of Things (IoT) technology to create a network of interconnected hydrophones. - Invest in the development of low-cost, high-resolution hydrophones that can be widely deployed, including in citizen science projects. - Invest in the development of low-cost, high-resolution particle motion sensors that can be widely deployed and integrated into acoustic propagation and exposure models. This is important for fish and invertebrates - linking to preserving marine resources - and is regularly omitted.
Light	Including coastal darkening, Coloured	- Quantify the intensity and distribution and trend of	- Global network such as GOOS and MBON are	- Existing marine observing networks need better integration of

	Dissolved Organic Matter (CDOM), artificial light at night (ALAN).	ALAN in marine environments. - Highlighting hotspots of light pollution and identifying areas most at risk of ecological disruption. - Quantify the effect of Impact on Direct glare, light trespass i.e. passing ships; Skyglow leading temporal disruption i.e. Nightly increase in sky brightness over coastal cities, disruption of daily life cycle in marine ecosystem; Seasonal variations in skyglow (especially during the winter months), bioluminescence suppression.	well-established for broader ocean monitoring but are only beginning to consider light pollution as a factor. - The International Dark-Sky Association plays a key role in the awareness and monitoring of light pollution, which indirectly affects coastal marine environments.	light pollution metric and define standard methods. For example, Satellite observations, such as NOAA Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band, provide global coverage of light pollution, including in marine areas. VIIRS is particularly useful in monitoring light pollution in coastal regions, where human settlements, industrial activities, and tourism contribute to ALAN. VIIRS can be also used to track light pollution from ships, which can be a significant source of ALAN. - Drones equipped with cameras or sensors to monitor light pollution to provide fine spatial data. - All-Sky Cameras (equipped with fisheye lenses) to provide continuous and quantitative data.
Biological	Includes faecal bacteria, pathogens, endocrine disrupting chemicals (EDCs) and antimicrobial resistant bacteria.	- Presence and Concentration; Spread and Transmission; Co-Occurrence with Antibiotics (in the case of	There is ongoing need for integration and expansion, particularly in the context of environmental AMR	The future observing capacity for marine biological pollution, including faecal material, endocrine disruptors, pathogens, and antimicrobial-resistant

		Antibiotic Microbial Resistance [AMR]), Bioaccumulation (for EDCs), Faecal Indicator Bacteria (FIB) Concentration (in the case of Faecal contamination). - Event base (i.e. sudden spills or discharge), Short-Term (Daily to Weekly) for phenomena that fluctuate rapidly, like faecal contamination after rainfall, pathogen outbreaks, plus Long-Term (Monthly to Yearly) for understanding i.e. trends and bioaccumulation. - Local (Near sources of pollution) versus global spatial scale where pollutants can be transported across large distances.	monitoring and emerging contaminants like endocrine disruptors. Faecal materials are better developed at local and regional scale. Overall monitoring endocrine disruptors is less mature compared to traditional pollutants. Environmental Monitoring and Assessment Programs: Agencies like the US Environmental Protection Agency (EPA), and European Environment Agency (EEA) have a specific monitoring programs to track endocrine disruptors like bisphenol phthalates, and pesticides while international research consortia (such as EU's NORMAN Network of reference laboratories, research centres and related organisations for monitoring of emerging environmental	bacteria, is expected to advance significantly due to innovations in technology, data integration, and global collaboration. Here's what the future might hold in these areas: - Faecal material real-time monitoring with advanced sensors stationed at key locations such as coastal outflows and river mouths, and marine recreational spot. - Satellite-based remote sensing combined to enhance the detection and mapping of faecal contamination over larger areas, where combination with AI algorithm could predict contamination events. Development of portable, user-friendly monitoring kits could empower communities improving spatial coverage. - Endocrine Disruptors: Advancements in analytical technique such as mass spectrometry, to screen for a broad spectrum of endocrine disruptors in marine environments. Development of *in-situ* bioassays

			substances) are assessing the presence of emerging contaminants, including endocrine disruptors	that can assess the biological impact of EDCs directly in the marine environment. - Overall Real-time monitoring, advanced analytical techniques, AI-driven predictions, and integrated One Health approaches will enable more accurate monitoring of faecal material, endocrine disruptors, pathogens, and antimicrobial-resistant bacteria.

6.7.3. List of Contributors

The list includes all experts that have contributed to this report by either answering the questionnaire, sending their inputs by email or joining the roadshows organised (names are listed by alphabetical order):

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6.7.4. Cross-Cutting Ideas

There are some cross-cutting areas or activities we have identified that this challenge will benefit from working together with others. Some examples:

- Having a sampling strategy where we combined efforts to reduce labour time, ship time and cost.
- Holistic approach when organising field campaign and studies. Marine pollution is not an isolated problem; it requires other variables to really understand how these environmental and societal variables are connected and how each variable affects the other.
- Combined efforts when engaging with industry, society and government to reduce stakeholders' fatigue and avoid duplication of efforts.

Chapter 7: Strengthening Resilience to Natural Multi-Hazards and Extreme Events

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7.1. Scope and Context

The UK is potentially vulnerable to a wide range of natural hazards, from the direct impacts of extreme weather events, likely to become more frequent and severe in a changing climate, to the global scale consequences of low-frequency, high impact hazards such as large-magnitude earthquakes and explosive volcanic eruptions. Marine science has a key role to play in strengthening future hazard resilience, including via: (1) integrated observational and monitoring technologies; (2) high-resolution reconstructions of past events to support future modelling and forecasting capabilities, particularly at the extremes, (3) an improved understanding of complex hazards (both meteorological and geophysical), in which oceanic environments contribute to feedbacks or cascading impacts; and (4) in developing coastal infrastructure and hazard management strategies designed for future environmental conditions. This chapter sets out the basis for these priorities and the role of future marine research infrastructure in meeting these needs. It also emphasises the opportunity for the UK in maintaining international leadership in marine hazard research, and in forging new technological capabilities and systems that can address hazard resilience within global partnerships (House of Commons Committee of Public Accounts, 2024).

As a maritime nation, coastal infrastructure is of key importance to the UK economy, and potentially vulnerable to sea-level rise and weather extremes driven by climate change. These vulnerabilities are summarised in a recent position paper from the European Marine Board (Figure 7.1) on Building Coastal Resilience, outlining negative ecological, economic and social impacts arising from ocean temperature increases, acidification and deoxygenation, and an increasing prevalence and impact of marine heatwaves, floods and storminess. Coastal settings are also vulnerable to impacts from fishing, aquaculture, waste disposal, transport, urbanisation, agriculture and coastal or offshore infrastructure, increasing the risks from eutrophication, invasive species, contaminants, seafloor disturbance and underwater noise. Population changes add to these pressures, resulting in degraded coastal environments with low resilience that cannot deliver valuable ecosystem services or recover from past impacts. To develop more resilient coastlines, we require both an improved understanding of current pressures, their interactions, and how to manage and mitigate their impacts, thus enabling the UK to develop an expanding blue economy while maintaining coastal resilience (Villasante *et al.*, 2023).

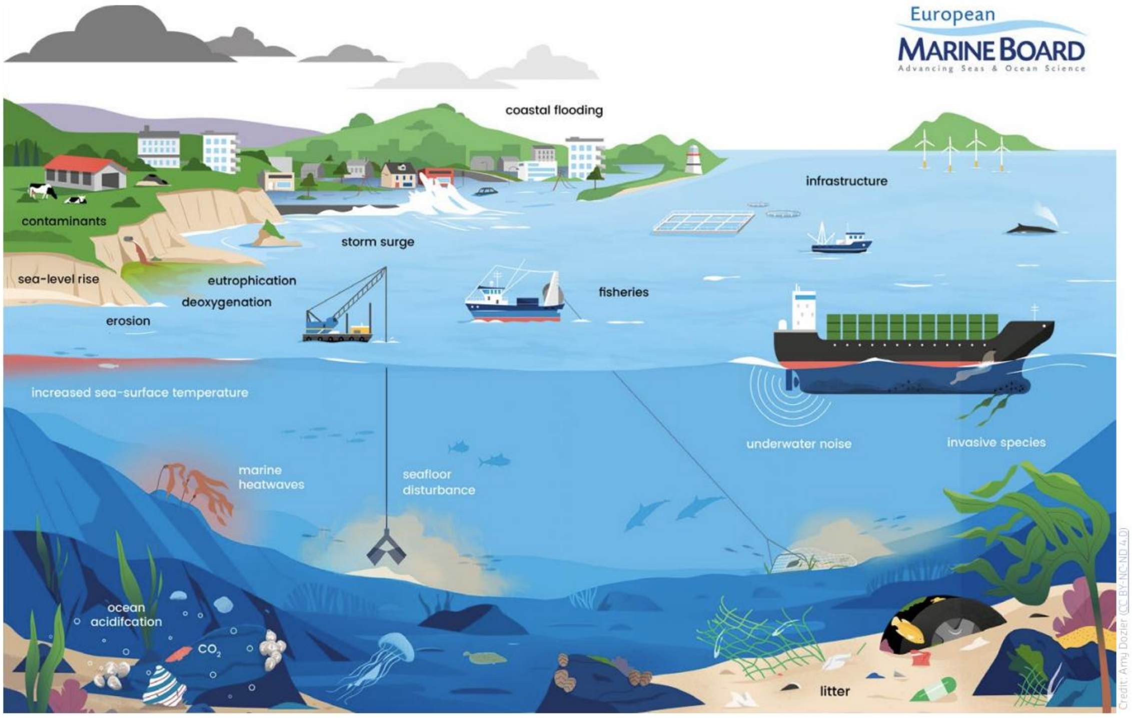

Figure 7.1: Overview of the multiple pressures affecting the coasts (EMB position paper number 27).

Beyond coastal settings, the UK as a whole is vulnerable to the impacts of natural hazards across a range of spatial and temporal scales, as also highlighted by the European Marine Board in a position paper entitled, ‘Marine Geohazards: Safeguarding society and the Blue Economy from a hidden threat’ (European Marine Board, 2022). The ocean preserves records of past events, plays a fundamental role in the generation of complex and extreme hazards (particularly climatic and meteorological events), and may lead to cascading hazards with far-reaching consequences. The global scale of such events is illustrated by the tsunamis from the Sumatran earthquake of 2004 and the Tohoku earthquake of 2011, the latter leading to the nuclear disaster at the Fukushima-Daiichi power plant in Japan. Distant geohazards, from earthquakes, landslides, volcanic eruptions and their associated tsunamis, may all affect the UK population and economy, including via disruption to supply chains, shipping, transportation and energy generation, and potentially increase the UK’s vulnerability to other risk factors. Such processes may also occur closer to the UK, with significant consequences even for events of modest magnitude, such as submarine landslides around UK coastlines or European volcanic eruptions (e.g. the Eyjafjallajökull eruption of 2010).

Lesser known marine geohazards may also pose challenges for coastal and offshore infrastructure development, including migrating sand waves, or mass movements driven by fluid release. Engineering projects, such as port expansions, energy installations or carbon capture and storage projects, may thus cause, and be affected by, unintended consequences through seafloor destabilisation.

The role of ocean processes in both geological and meteorological hazards thus needs to be assessed using a multi-hazard and impact-based approach. Currently, there is no standardised framework to plan for, manage and monitor the range of geohazards affecting the UK, and their impacts on both marine and terrestrial environments. With future growth in offshore infrastructure, there is a need to both understand the risks posed by low-frequency but high-impact natural events and high-frequency lower magnitude events, which cumulatively may have large impacts.

7.1.1. Definitions

For the purposes of this document, the definitions of natural hazards, resilience and extreme events follow the established glossary of the United Nations Office for Disaster Risk Reduction (UNDRR, 2023) terminology for disaster risk reduction and the multi-hazard and multi-risk terminology adopted by the MYRIAD-EU project (Disaster Risk Gateway, 2022). The UNDRR define a hazard as 'A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation', which includes both physical and biogeochemical processes. Hazards that are predominantly associated with natural processes and phenomena are referred to here and by the UNDRR as **natural hazards**. The UK Government Resilience Framework (UK Government, 2023) defines **resilience** as 'the ability to anticipate, assess, prevent, mitigate, respond to, and recover from natural hazards, deliberate attacks, geopolitical instability, disease outbreaks, and other disruptive events, civil emergencies or threats to our way of life.' There is not a generalised UK government definition for an **extreme event**, so we follow the definition of extreme weather events, defined in the Government Resilience: Extreme Weather report (House of Commons Committee of Public Accounts, 2024), 'events that are significantly different from the average or usual pattern' and add the NOAA definition (NOAA, 2020), 'a time and place in which weather, climate, or environmental conditions – such as temperature, precipitation, drought, or flooding – rank above a threshold value near the upper or lower ends of the range of historical measurements.' To acknowledge that a single hazard might not be extreme but still be considered part of an extreme event, we have adopted the definition of **multi-hazard** provided by the UNDRR as 'the selection of multiple major hazards that the country faces, and the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects'.

7.1.2. Natural Hazards and Extreme Events: The Role and Significance of the Marine Environment

The ocean covers more than 70% of the Earth's surface and plays a fundamental role in the modulation of the global climatic system, including extreme weather events and their terrestrial impacts. A range of hazard processes also occur directly within the marine environment, and on or beneath the seabed, via both meteorological and geological processes. These have the potential to cause major impacts to coastal environments and offshore infrastructure, on scales ranging from local to global. Marine hazards are characterised by their potential to trigger far-reaching, cascading impacts (such as tsunami generation) and by the unique challenges they pose for forecasting, monitoring, and management compared to wholly terrestrial hazards (e.g., onshore volcanic eruptions or landslides). In some cases, secondary hazards like tsunamis may pose a greater risk to communities or ecosystems than the initial event itself. For example, a moderate-sized submarine earthquake, which would not be considered a tsunami risk, may trigger an underwater landslide that goes undetected, which in turn then triggers a tsunami that is anomalously damaging relative to the size of the initiating event. Where hazards occur simultaneously or in quick succession, they can interact with each other and lead to compound far-reaching socio-economic impacts that remain challenging to forecast and mitigate. To improve resilience, marine hazard research must be cross disciplinary, spanning oceanography, geology, geophysics, meteorology, biology, engineering, spatial planning, policy, economics and the social sciences. Future management and monitoring strategies must also look to technological innovations, such as novel observational and monitoring strategies, to address the current imbalance between terrestrial monitoring – utilising a variety of ground-based and satellite technologies – and marine monitoring, which remains a global knowledge gap. Marine hazards are also increasingly recognised as a blind spot in regional and national risk assessments.

The ocean floor also provides access to an important global archive of past hazard events, particularly important for reconstructing extreme and rare events with global impacts. This is the case both for understanding climatic and meteorological extremes, and for reconstructing geophysical hazards, such as past records of volcanic eruptions and some earthquakes. Sub-seafloor records of the Earth's past and present-day structure have been fundamental to developing our understanding of Earth's systems, and this includes the factors that influence the frequency and magnitude of hazard events, as well as the signatures of those events themselves. Nevertheless, there remain many parts of the world, particularly the subduction zones and volcanic arcs of the western Pacific and Indian oceans, with major gaps in our knowledge of past events and sub-surface structure and processes. These gaps impact on hazard planning and preparedness, as was well demonstrated by the lack of an integrated detection and warning system for the Indian Ocean tsunami of 2004. Our capacity to survey and sample at and beneath the ocean floor thus remains fundamental to improving our knowledge of the planetary processes that govern natural hazards, and in understanding the frequency, magnitude and impacts of past events. The seafloor archive, however, is incomplete due to erosion and reworking, and will likely be biased towards high magnitude, low frequency events.

The natural hazards relevant to the UK, and for which the ocean plays a key role either as a source of that hazard, or as a route to improving our knowledge and resilience to that hazard, are thus diverse and span a range of spatial scales. These range from local events that impact UK coastlines directly, with consequences for infrastructure and the potential to develop into technological hazards, to processes impacting the continental shelves and offshore infrastructure, through to global events with consequences for the entire UK population. A summary of these varied processes is outlined in Table 7.. Biological hazards arising from eutrophication, deoxygenation, and invasive species are covered by other chapters and are not discussed further here.

Table 7.1: Overview of natural hazards relevant to UK.

Hazard	Description
Coastal erosion and landslides	Coastal erosion is the physical reduction of land mass at the coast that results from the marine, fluvial and landsliding processes interacting with the coast, resulting in changes to the shoreline and damage to coastal infrastructure and developments across a range of spatial and temporal scales.
Contaminants and litter	Through the interaction of currents, tides and winds, some coastal areas are prone to the deposition and accumulation of pollutants and natural and plastic floating debris. Contaminants can cause reduction in ecosystem function or collapse and can impact sectors including fisheries, tourism, and aquaculture.

Earthquakes	Earthquakes are the sudden release of strain in the Earth's crust, typically in the form of a brittle rupture. This generates ground shaking and, in shallow earthquakes, may cause substantial deformation of the overlying surface. This may generate tsunamis directly, or via the triggering of submarine landslides. The largest earthquakes occur at or near plate tectonic boundaries, particularly at destructive plate margins.
Flooding, storm surges, waves	Rising sea levels increase the exposure of coastal communities to episodic flooding due to tides, storms, and waves. The interaction between storm surges, waves and mean sea-level changes are an evolving research area. Higher flood levels increase the risk to communities and infrastructure, with potential impacts on tourism, recreation, coastal energy and transportation.
Fluid activity	Fluid flow through marine sediment, caused by a variety of processes including burial, fluid migration, biogeochemical processes, and hydrothermal activity may generate mud volcanoes and pose hazards to marine infrastructure or during marine drilling or trenching operations.
Marine heatwaves	Marine heatwaves (MHWs) have increased in intensity and frequency globally over the last decades. This trend is expected to continue into the future, with the Arctic Ocean being one of the regions to experience the largest increase in frequency of MHWs. MHWs are characterised by discrete periods of anomalously high ocean temperatures that last for more than five days with temperatures exceeding the 90th percentile of the 30-year historical baseline. They have detrimental ecological implications, including mass mortalities, harmful algal blooms, shifts in species' ranges, and altering food webs and species interactions.
Meteotsunamis	A meteotsunami is generated by sudden changes in atmospheric pressure. These changes can occur during the passing of squalls or storm fronts, resulting in waves with tsunami-like characteristics but with an atmospheric rather than geophysical origin (US Department of Commerce, 2025).
Migrating bedforms	In areas with strong currents or tidal regimes, where the seafloor is covered by loose material, sand waves may form and migrate. They occur in many environments, including shallow coastal seas, straits, canyons and channels, posing a threat to seafloor infrastructure, such as submarine cables, wind turbines and pipelines.
Ocean temperature	Global mean sea surface temperature has changed by 0.6°C since 1980, though regional variability means this is more or less extreme in some locations. Warming affects ecosystems in different ways including changes in species composition, changes in the range of mobile species, loss of kelp forests and time of reproduction and migration of species. These changes have poorly understood consequences for the functioning of ecosystems.

Rip currents	Rip currents are strong flows of seawater travelling perpendicular to the shoreline and out towards the sea; they can change rapidly due to variations in waves, tidal levels and beach morphology. They are the most common hazard to coastal recreation users as they appear calm on the surface yet pull people out to sea. They are a major global cause of accidental drowning on beaches; the majority of UK lifeguard incidents involve individuals caught in rip currents (Met Office, 2020).
Sea-level rise	Sea-level rise is a result of thermal expansion due to ocean warming and the loss of land-based ice from glaciers and ice sheets. Between 1901 and 2018, global mean sea level increased by 20 ± 5 cm, with increasing rates over the past couple of decades. Uncertainty in future projections make it difficult to understand exactly where and how severe impacts will be. Potential impacts include flooding and increased rates of other hazards including salination of aquifers, coastal erosion, landslides, and the displacement or collapse of intertidal flats, tidal salt marshes, low subtidal foreshores, and dune ecosystems.
Submarine mass movements	Submarine slopes are often composed of unconsolidated, water-saturated soft-sediment. The homogeneity of the seafloor over large areas can result in extensive failures and highly mobile mass movements, which may damage submarine infrastructure and generate tsunamis. The triggers for submarine landslides are poorly constrained, but include overpressure between grains, earthquakes, tidal cycles, over-steepening, large sediment inputs and anthropogenic activity, or a combination of these processes, acting over a range of timescales.
Tsunamis	A tsunami is a succession of waves of long wavelength generated by a sudden displacement of water. Tsunamis may be triggered by processes including earthquakes, volcanic eruptions, submarine or subaerial landslides, and meteorite impacts. Tsunami impacts depend on the volume and size of the original displacement, the proximity of coastlines and infrastructure, and the shape and morphology of the coast and seafloor.
Volcanoes	Volcanism occurs where melts forming in the Earth's mantle are able to reach the surface, both at constructive and destructive plate boundaries, and in intraplate hot-spot settings. Coastal, island and submarine volcanoes may occur in all these settings. Volcanoes present variable hazards, strongly linked to the composition of magma they erupt, eruption magnitude, and explosivity, and these may be further modified by interaction with water. The impacts of volcanic eruptions range from local to global scales, the latter via atmospheric and climatic processes.

7.1.3. Governance of Marine Hazards and Extreme Events in the UK

Various partnerships aim to coordinate management and resilience to natural hazards in the UK. The Natural Hazards Partnership (NHP; Figure 7.2), a consortium of government departments and agencies, trading funds, public sector research establishments and bodies, research council institutes and charities, offers expert insights on various natural hazards, developing advanced hazard impact models and supporting technology. The new UK National Climate Science Partnership (UKNCSP; Met Office, 2021) will provide the foundations to enable the UK to be a global leader in climate science for climate solutions to tackle climate change and its impacts, which includes the potential for a greater prevalence and extremity of natural hazards (e.g. those associated with meteorological extremes and sea-level rise). The UKNCSP seeks to combine the UK's wide-ranging capabilities in climate observing and prediction to shape a world-leading, strategic partnership that will work with the public and private sector to ensure decision-makers and businesses have access to the climate information they need, in order to build urgent resilience and adapt to the pressing challenges of the coming decades.

Figure 7.2: Members of the Natural Hazards Partnership as of August 2024 (https://www.ceh.ac.uk/natural-hazards-partnership).

7.1.4. State of the Art in Marine Hazards and Extreme Events Research in the UK

The United Kingdom is a world leader in analysing marine hazards and extreme events, with world class infrastructure and observatories driving internationally important research in areas including the impacts of human infrastructure on marine ecosystems, informing spatial planning and marine engineering, climate modelling and forecasting (e.g., predicting marine heatwaves and oceanic responses to climate change), and (sub)seafloor sampling, mapping and modelling to forecast earthquakes, volcanic eruptions and tsunami generation, and the vulnerability of marine infrastructure such as global communication cables to such processes. The use of machine learning and digital twinning plays an important part in this data-intense research.

Currently sustained ocean observatories in the UK feed into meteorological models used to forecast storms and weather, and experts across the scientific spectrum contribute to the National Risk Register. For example, to enhance our ability to assess compound events, the Met Office has invested in a Regional Environmental Prediction (REP) modelling approach, the framework for which will provide multivariate information from the atmosphere, land, waves and ocean around the UK (Met Office, 2021b). Investment in science and computing has made the UK a world leader in climate change research, but as we see from recent extreme weather events worldwide, understanding and predicting climate change is not enough. To respond to the threats posed by a rapidly changing climate, climate science needs to move from defining the problem to enabling solutions.

The UK is also a world leader in many aspects of marine hazards and extreme events research, both in UK waters and around the world. These activities include but are not limited to human and infrastructure impacts on ecosystems, climate and ocean modelling and forecasting, tsunami generation and modelling of resultant hazards, marine geohazards including volcanoes, earthquakes, submarine landslides, turbidity currents, and other shallow hazards, marine heatwaves, marine engineering and in applying artificial intelligence to more efficiently process marine and modelling datasets and develop new approaches for hazard forecasting and mitigation. It is likely that the UK will continue to lead in these areas as well as expand into new and emerging spaces as the develop.

7.2. Anticipated Scientific Developments By 2040

A key priority for strengthening hazard resilience, across the full range of processes in Table 7., is a need to define baselines appropriately so that the impacts of hazards, including those exacerbated by climate change, can be accurately measured and monitored. This is becoming urgent, given the growing impacts of meteorological extremes, and an accelerated need for marine resources (minerals and energy), where sound ecological baselines and understanding of Earth processes are required to underpin assessments of impacts, risks and opportunities for marine net gain and security for infrastructure and energy. Ongoing work in this field, both in the deep and shallow marine environments, has led to a scientific consensus that not enough is known about marine ecosystems and natural geohazards to underpin marine planning with confidence. In many cases, a strategic and regional approach is needed to understand ecological functions and sub-sea processes, with hazards often caused indirectly and/or from processes in the far-field.

In many instances, improved planning, mitigation strategies and modelling of hazards and their impacts, important to a range of coastal and offshore infrastructure, rely on high resolution observational and sampling datasets, particularly in coastal and nearshore environments. Global efforts, such as the international Seabed 2030 programme (to map the ocean floor at 100 m resolution), are not sufficient to develop UK resilience across the spectrum of processes in Table 7.. Greater coverage of high-resolution marine datasets (e.g. monitoring temporal seabed evolution, including pre- and post- event data and seabed morphodynamics, are required to advance hazard management strategies. High-resolution sub-seafloor datasets, with more comprehensive spatial coverage and including sampling capabilities, are also fundamental to advancing understanding of processes and mechanisms driving geological hazards (such as those linked with submarine mass movements, seismic activity and volcanism), and in improving records of past extreme events and their consequences.

We expect significant technological development by 2030, particularly in ocean observatories, communications and sensors. There are several seabed observatories currently in existence – these are the pilot projects that will identify the most efficient and useful ways to measure parameters in the deep ocean and are likely to enable more and better observatories in the future. Developments in communications, particularly the likely existence of global Wi-Fi internet coverage by 2030, would make transmitting data from sensors at observatories both possible and inexpensive and increase the current capability for real-time monitoring of hazardous regions. To ensure information is appropriate and accessible, digital technology to remotely control sensors improving the efficiency of data collection, and dashboards with data processing capability to alert or warn of a hazard event, are emerging but require integration to become transdisciplinary. Increased satellite coverage and resolution, along with an increasing diversity of satellite-derived products and processing algorithms, are expected over the next few decades. In this context, Destination Earth (DestinE; European Space Agency, 2022) is an ambitious initiative of the European Union to create a digital model of Earth that will be used to monitor the effects of natural and human activity on our planet, anticipate extreme events and adapt policies to climate-related challenges. Using innovative Earth system models, cutting-edge computing, satellite data and machine learning, Destination Earth will allow users to explore the effects of climate change on the different components of the Earth system, together with possible adaptation and mitigation strategies.

Linked to technology, recent advances in cable sensing, including methods that allow for the detection of signals of ocean and geological processes using existing telecommunications cables (Distributed Acoustic Sensing – DAS), are opening new routes to deep-ocean time-series measurements, complementing a range of datasets acquired over recent decades (e.g. via ocean bottom seismometers and pressure gauges). Such approaches hold the potential to extend global coverage of real-time geophysical data acquisition, including real-time monitoring of ocean currents, seismicity and volcanic activity. The focusing of these efforts in the most hazardous regions, including those with high exposure to global shipping and communications routes, will enable better targeting of future data collection efforts.

7.3. Key Science Questions, Knowledge Gaps and Uncertainties

The diversity of topics covered by this theme make it impossible to highlight all the scientific questions that will be a priority in 2040 in this document. Across the workshops many topics were raised, including but not limited to: earthquake precursory conditions, volcanic and submarine volcanic monitoring and records, higher resolution coastal measurements to enable climate impact forecasting, the impact of climate change on essential ocean processes (e.g. the Atlantic Meridional Overturning Circulation), enhancement of existing hazards by climate change, threats from infrastructure to the natural environment, tsunami risk and modelling and ocean drivers for non-marine regimes. However, three general priority themes emerged from these discussions that crosscut individual scientific disciplines:

i) **Identification of multi-hazards and extreme events:** the ocean is a blind spot when it comes to identifying potential future hazards or extreme events, due to the lack of high-resolution mapping (particularly in near coastal zones and the deep oceans), ocean monitoring and the fact than many of these hazards have not occurred yet (emerging hazards) or have not been experienced or recorded on historical timescales. There has also historically been a focus on the largest and most catastrophic events, however, smaller events that occur regularly are much less well characterised or recorded, even though cumulatively they may have a larger impact overall. There is also a knowledge gap in understanding the, often complicated, connections and triggers between primary and secondary hazards in order to predict the impact they may have and a lack of models that connect the land to the marine realm.

ii) **Timing and frequency of hazards and extreme events:** key to understanding the risks of hazards and extreme events is knowing their likely recurrence intervals and forecasting when events might occur. For almost all of the hazards in Table 7., this is currently not possible. We lack an understanding of both the fundamental earth processes that drive catastrophic events, for example major volcanic eruptions, and the processes and preconditioning that may prime and trigger events, for example, submarine landslides. Our ocean models are also not high enough resolution, or lack the appropriate constraining data, to allow accurate forecasting of extreme events like marine heatwaves, and we do not have enough observations to understand the impacts of these events on the natural environment. One key aspect in a changing climate is the potential link to how climate change may trigger marine hazards and cascading consequences (e.g., by changes in ocean temperature and currents causing more storm events, with associated run-off and sediment remobilization processes, groundwater charging, etc.). Questions remain on whether a climate-induced increase in marine hazards and geohazards can be identified (and quantified), and whether the probability of their occurrence can be modelled. To model geological processes, larger timescales (hundreds to thousands of years) are needed for both hindcast and predictive models.

iii) **Resilience:** Resilience depends on the exposure to hazards or extreme events, as well as the impacted community or ecosystem's ability to survive and recover from it. In terms of ecosystems, we lack the detailed understanding of community thresholds and tipping points, making the impacts of events hard to predict or quantify. For communities, we do not collect as standard, the types of data essential for understanding vulnerability to specific hazards uniformly across the planet, and we expect the ways in which communities are vulnerable to change, for example as more services move online, or as transport mechanisms change. We also lack an understanding of the interaction of hazards or extreme events that may amplify or alter one another, with most studies focussing on single events rather than compound or cumulative impacts.

Achieving these objectives requires a combination of sustained and individual experimental data acquisition, as well as the potential to install infrastructure then communicate data in real time to land (for monitoring of hazards). Sustained observation is essential for monitoring but will mean different things in different situations. For example, sustained seismic and deformation monitoring are likely to be the most useful for volcanic and earthquake-generating settings, while repeated photographic surveys alongside geochemical and ocean measurements would be the most important for understanding ecosystem impacts of a marine heatwave or anthropogenic disturbance. Much of this work will also require the physical sampling of ocean waters, organisms and the seafloor and sub-seafloor, and there is a requirement for both individual sampling campaigns as well as sustained return sampling in some situations.

It was also highlighted that with increased amounts of data, particularly with sustained observations, there would need to be increases and changes in data storage, sharing and accessibility in future. Not all data types are currently supported by standard repositories like the British Oceanographic Data Centre, and with increasingly diverse and new datasets and types, there would either need to be an expansion of existing data sharing capability and platforms or the development and support of new platforms. For assessment, forecasting, warning and scenario analysis of hazards, new connections with national agencies would need to be established where these do not currently exist.

7.4. Observation and Product Requirements

The diversity of hazards in the ocean requires diverse measurements on variable time and spatial scales, as well as bespoke platforms for data sharing and modelling future hazard scenarios. Strengthening the UK's resilience to natural multi-hazards and extreme events in the marine environment will require a step change in the quality, resolution and coverage of observational data and resultant products. A robust and forward-looking observational infrastructure must integrate geophysical, geological, oceanographic and ecological data to support early warning, hazard characterisation and assessment, impact forecasting and risk-informed decision making.

Across all of these topics, in order to improve resilience, monitoring and anticipation is critical. Monitoring involving the sustained measurement of fundamental parameters will allow forecasting of certain hazards on longer timescales, enabling us to develop more resilient infrastructure, will provide warnings of imminent hazards, in some cases allowing either the cessation of an activity before it develops or the evacuation of regions likely to be impacted where the source cannot be controlled, and will improve our understanding of potential precursors and triggers of hazardous phenomena so they can be mitigated.

7.4.1. Assessment, Forecasting and Characterisation

To enhance the assessment and forecasting of marine hazards, comprehensive geological and geophysical characterisation of the subsurface through repeat surveying is essential. This includes acquiring high-resolution active and passive seismic data, potentially taking advantage of existing fibre optic cable networks, alongside controlled-source electromagnetic surveys and gravity and magnetics measurements. Geological sampling through coring and drilling will remain critical for understanding the processes that lead to hazardous conditions, reconstructing past events and estimating recurrence intervals and magnitude-frequency relationships. This information will also help to identify their precursors and to assess hazard potential based on current conditions. These data must be supported by infrastructure to deliver long-term sustained observations, i.e., observatories capable of capturing dynamic changes across relevant spatial and temporal scales.

An enhanced spatial and temporal understanding of the coastal and shelf interface is also required, through high-resolution bathymetric, topographic and geophysical data across shallow, subtidal, intertidal and supratidal zones, particularly in high-risk regions such as estuaries and low-lying coasts. *In-situ* observations of waves, tides, storm surges and changes in morphology during extreme events will provide essential insight into erosion, overtopping and coastal inundation, to characterise the critical region where ocean and land interact, and identify thresholds for storm-driven coastal erosion and flooding. Innovation in sensors and real-time monitoring technology will lead to extended observations of seismic, volcanic and oceanographic processes required to support multi-hazard assessments and early warning systems of precursors to extreme events. This data is necessary to quantify the magnitude and temporal phasing of processes across the spectrum of marine hazard conditions, to inform, develop and constrain predictive modelling, and to develop improved resilience and management strategies.

7.4.2. Modelling

Improved modelling capabilities will be vital to predict the occurrence of marine geohazards, and the potential impacts of factors including climate change, storms, waves, flooding, and marine heatwaves. This will require improved boundary conditions and higher resolution measurements of processes triggering and acting within hazardous events. Furthermore, higher spatial and temporal resolution measurements of deep ocean and coastal processes will be needed, including temperature, currents, tides, waves and turbulence, and from seafloor and sub-seafloor surveying and sampling. Increased global sensor coverage, particularly in sensitive locations such as the seafloor and subseafloor and expanded use of satellite-derived data is needed, to support both oceanographic and geological purposes. These data will help to identify changes in the magnitude and frequency of marine hazards driven by climate change, storms, waves, flooding, and marine heatwaves, and of geohazards, to enhance future hazard prediction and mitigation.

7.4.3. Understanding Ecosystem Impacts

An expansion of physical observations and long-term sampling, combined with innovative habitat mapping and AI-based predictions, will be required to enhance the understanding of ecosystem responses to marine hazards and extreme events. *In-situ* observations of community response to disturbances, including anthropogenic hazards, will be necessary to better characterise ecosystem thresholds and tipping points, improve understanding of ecosystem connectivity, and predict community structure and vulnerability, particularly in data-sparse regions.

7.5. General Description of Key Capabilities

Figure 7.3 illustrates the range of spatiotemporal scales in marine systems that need measuring to address the challenge of Strengthening Resilience to Natural Multi-Hazards and Extreme Events. The range of spatial (horizontal dimension) and temporal scales of all the marine processes identified varies from the order of meters to thousands of kilometres and from minutes to hundreds of years. In addition, some of the processes have an additional vertical dimension representing the depth below the ground or seabed surface. The values for this vertical dimension are also shown in Table 7., with values of 0 km indicating that these are above ground level and positive values indicating the dimension that measurements will need to be taken for each hazard/process listed.

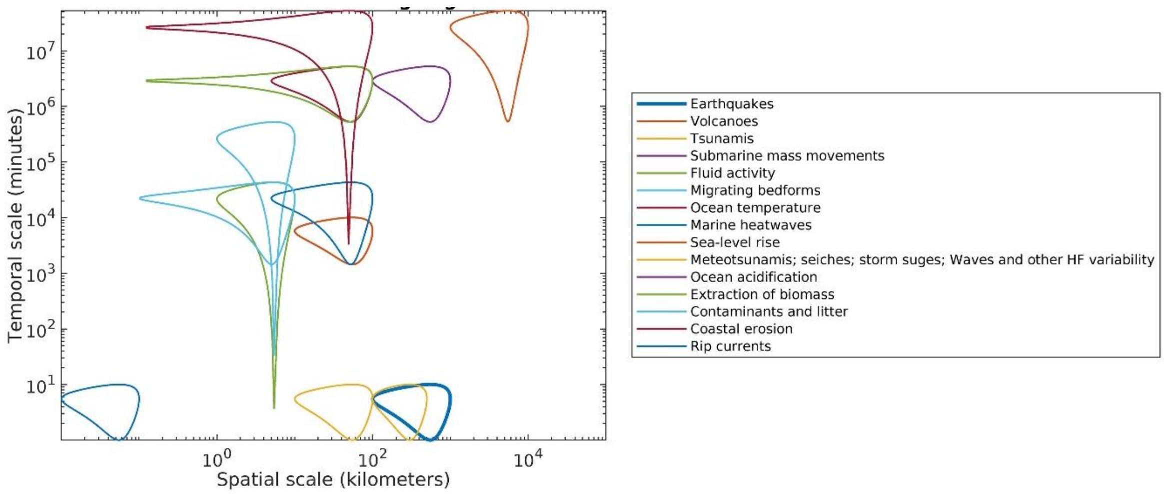

Figure 7.3. Measuring across spatiotemporal scales in marine systems is required to address the challenge of Strengthening Resilience to Natural Multi-Hazards and Extreme Events. This figure illustrates the temporal and spatial scales of the different hazards discussed. An indication of the subsurface vertical scale is given by the thickness of the coloured lines: the thicker the line, the deeper in the subsurface. The order of magnitude values used for this plot are also shown in table format in this section.

Table 7.2: Order of magnitude values used to create the plot shown in Figure 7.3. Where z_dim is the vertical dimension in the subsurface, X_{min} and Y_{min} the spatial minimum and maximum scale and T_{min} and T_{max} for temporal scale for each hazard.

Hazard Name	**z_dim (km)**	**X_{min} (km)**	**X_{max} (km)**	**T_{min} (min)**	**T_{max} (min)**
Earthquakes	1000	100	1000	1	10
Volcanoes	100	10	100	1440	10080
Tsunamis	1	100	500	1	10
Submarine mass movements	1	1	10	1	525600
Fluid activity	0	1	10	1	43200
Migrating bedforms	0	1	10	1	525600
Ocean temperature	0	5	100	525600	5256000
Marine heatwaves	0	5	100	1440	43200
Sea-level rise	1	1000	10000	525600	52560000
Meteotsunamis; seiches; storm surges; Waves and other HF variability	1	100	10	1	10
Ocean acidification	0	100	1000	525600	5256000
Extraction of biomass	0	0.1	100	525600	5256000
Contaminants and litter	0	0.1	10	1440	43200
Coastal erosion	0.1	0.1	100	60	52560000
Rip currents	0	0.01	0.1	1	10

The hazards covered by UK researchers are so diverse they will require a broad range of future infrastructure. There is an enthusiasm to embrace autonomy, for the increased range and survey extents possible as well as the reduced cost and environmental impact of using a vessel. However, there is also a recognition from the community that many activities, in particular some geophysical surveys and physical sampling, cannot be achieved without a vessel. For example, to better understand the frequency of past events, deeper paleo records need to be sampled and/or observed, which often involve bigger equipment that imposes constraints on the size of the vessel that can be used.

7.5.1. Observational Infrastructure

Multi-platform (i.e. autonomous, research vessels, Earth Observation and *in-situ*), multi-scale and multidisciplinary observations are needed to monitor, understand and predict changes in marine systems, and for early-warning systems for natural multi-hazards.

Mobile autonomous platforms are likely to form a large part of the effort to acquire better spatially distributed measurements and may, alongside traditional measurements with buoys, provide monitoring capability for some hazardous phenomena, particularly those associated with climate impacts on the ocean, while deeper submergence vehicles able to complete longer missions will contribute to better mapping of and characterising the ocean floor. New sensors are already emerging to assess waves and water levels where they interact with land to better understand the pathway of coastal hazards that impact communities and infrastructure.

Research Vessels will continue to be required for most physical sampling (some autonomous water sampling is possible) and geophysical surveys. For monitoring, repeat measurements made with either autonomous platforms or vessels may prove enough for some hazards, while others are likely to require a combination of dedicated observatories in high-risk zones, combined with remote observations from satellites and potentially measurements made using the existing subsea cable infrastructure. Research vessels will be needed for deploying and retrieving instruments making long-term measurements, some autonomous vehicles, and to retrieve data from seafloor/sub-seafloor observatories (e.g. seismometers, acoustic/geodetic instruments, pressure sensors, other seafloor or borehole instruments).

Earth Observation (EO) is the gathering of information about planet Earth's physical, chemical, geological and biological systems via remote sensing technologies, usually involving satellites carrying imaging devices (EU Scientific Commission). It is essential for understanding natural hazards, particularly in multi-(hazard-)risk contexts. Data from EO has rapidly become widely available and substantially easier to use due to the steep decline in the cost of imagery and the deployment of machine learning algorithms. By leveraging this EO data, we can address complex interactions between hazards and enhance resilience. Products derived from the Global Navigation Satellite System underpin many hazard and risk assessments: e.g., monitoring deformation of the solid Earth, monitoring Earth rotation, ionosphere and troposphere and variations in the hydrosphere.

7.5.2. Digital Infrastructure

All observations need to feed into **open data services** such as the European Marine Observation and Data Network (EMODnet) and Copernicus Marine Environmental Monitoring Services (CMEMS) in order to monitor the success of implemented coastal resilience solutions and fulfil governmental monitoring requirements. A key challenge is the integration of socio-economic data with physical, biological, geological and chemical data, especially given the significant data gaps that exist for social datasets. Moreover, all existing long-term physical, biological, geological and chemical datasets should be integrated into these data services to gain a historical perspective. This will require new methods to overcome the challenges of managing and extracting information from large, diverse datasets spanning multiple disciplines and comparing datasets with different resolutions and timescales.

To better anticipate plausible future hazards scenarios, we will need to develop a **new generation of models** to help interpret and provide robust and innovative methods for long-term hazard assessments and/or short-term forecasting of marine geohazards where possible. This approach needs to cover all time scales, from seconds to hours (storms, flooding, landslides, earthquakes, tsunamis), days to years (coastal erosion, volcanic eruptions, migrating bedforms, fluid activities), and years to millions of years (e.g. longer-term seafloor deformation). Modelling local and regional coastal change is critical for understanding how different pressures manifest and interact. Models need to be validated through continuous observations and monitoring of key indicators to ensure accuracy. Global and ocean basin climate change models need to be downscaled to a regional level to help inform the development of protection and adaptation measures and help decision-makers to mitigate the compound impacts of interconnected pressures. The European Digital Twin Ocean (Mercator Ocean, 2022), supported by short- and longer-term models and open data, should advance the prediction of the impact of climate change and human activities on coastal systems and the effectiveness of interventions. Advances are needed in the development of multi-hazard early-warning systems that consider multiple, interacting coastal pressures. Research infrastructures should contribute to environmental monitoring for the development of such systems.

The deployment of widespread 5G technology can significantly enhance flood detection systems by enabling faster, more reliable communication between sensors and monitoring systems. With its low latency and high bandwidth, 5G allows real-time transmission of large volumes of data from remote sensors, improving the accuracy and timeliness of warnings. Additionally, 5G technology supports the integration of cutting-edge technologies such as Internet of Things (IoT), Artificial Intelligence (AI), and edge computing, enabling more in-depth analysis and prediction models that can better assess flood risks and provide timely alerts to local communities and authorities.

7.5.3. People, Skills and Partnerships

Environmental change is occurring at such scale and pace that we must face the increased risk of natural hazards as an extraordinary challenge. To strengthen resilience to natural multi-hazards and extreme events, communities need to recognise their role in this and take responsibility. That can be achieved by better science, better science communication (e.g., events by agencies or learned societies aimed at the public/local community), and better science education (e.g., Frontiers for Young Minds: Natural Hazards in the Ocean; Hillman, Bull and Watson, 2023) to make people more aware, better prepared and more confident in their own understanding of hazards. That requires better skills training (including at sea) for both scientists and for wider communities, including an improved understanding and communication of risk and uncertainty (e.g. event magnitude, likelihood, exposure, extreme events, and short-term variations versus long-term change). The complexity of Earth processes in the marine world, and of the complexity in roles of local and national authorities in investigating and managing associated hazards, also needs to be well communicated and to feed into policy frameworks and risk management strategies. There are tools can be used widely (using EO data, for example) to democratise and diversify science and the scientific community

(Nagaraj, Shears and de Vaan, 2020), while access and dissemination of other tools and processes involved in marine research is more challenging but should be a priority to broaden participation.

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Chapter 8: Sustainable Blue Economy and Ecosystem Services

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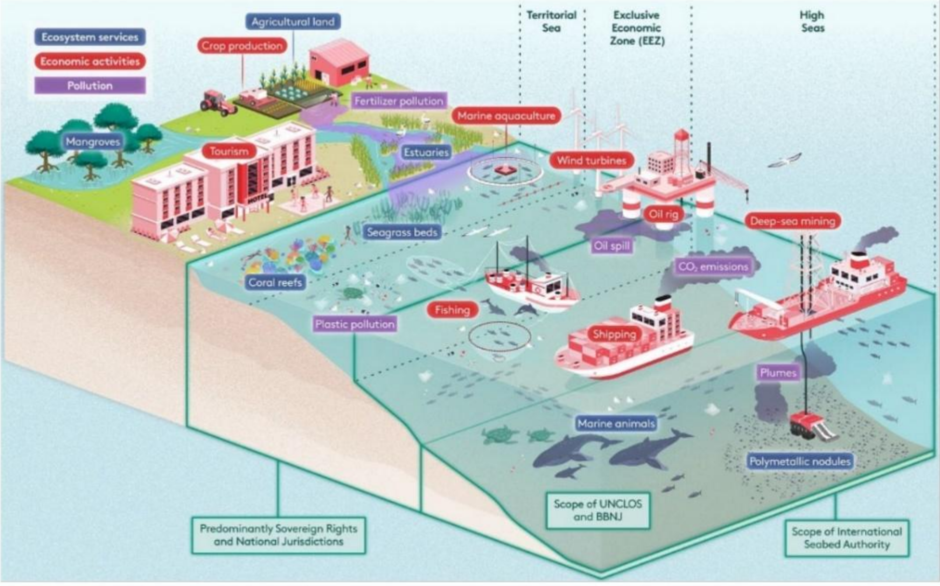
8.1. Scope and Context

The blue economy (BE) explicitly recognises the use of the ocean space and its resources as an essential component of global economic growth and prosperity. At the centre of the concept is the conscious decoupling of socio-economic development and environmental degradation, and while the concept has many definitions and a range of names (Sustainable Blue Economy, Sustainable Oceans Economy, Blue Growth), it is a significant deviation from the past paradigm where the marine environment is an unregulated source of value and a waste dumping location with costs, financial and environmental, generally externalised from economic calculations. The BE is predicated on the utilisation of a range of provisioning and non-provisioning ecosystem services without depleting the natural capital on which they depend. Although estimates of the value of the BE vary, it is clear that the ocean plays a crucial role in the global economy; around 90% of global trade is moved by ships (International Chamber of Shipping, 2020), 3 billion people rely on the ocean for a significant proportion of their protein intake (Food and Agriculture Organisation of the United Nations, 2022), and the production of food from the ocean employs an estimated 237 million people (Teh and Sumaila, 2013). Further to their direct economic value, the ocean provides a range of ecosystem services crucial to humanity's wellbeing such as absorbing excess heat generated by global warming, providing 50% of the planet's oxygen (Sekerci and Ozarslan, 2020), drawing down globally significant quantities of carbon dioxide from the atmosphere (approx. 3 billion tonnes per year; Friedlingstein *et al.*, 2022), and protecting coastal communities from some natural hazards. It is also home to a number of economic activities, such as tourism, renewable and non-renewable energy generation, telecommunications (via seafloor cables) and resource extraction (Figure 8.1). Between now and 2050, it is expected that the level of activity, the value and societal importance of the BE will significantly increase, with some estimates showing a doubling in the economic value by 2030 alone (Organisation for Economic Co-operation and Development, 2016).



Source: Authors.

Figure 8.1: The ocean economy, comprising marine ecosystem services, economic activities, selected polluting effects and international governance zones (Almeida and Reitmeier, 2024).

The knowledge requirements of the blue economy can be effectively conceptualised into two forms:

1. Those required by society to ensure that industries within the blue economy do not deplete or negatively impact the natural capital on which they and a range of other (global) stakeholders depend. This requires that the impacts of the industries are effectively monitored and fed back to regulators within appropriate timeframes to avoid significant or unacceptable impact. When considering this requirement, it is crucial to understand the global nature of many sectors, such as the fishing industry, and in many cases their operation beyond national boundaries.

2. Those required by participants in the blue economy (including those investing within the BE) to ensure sustainability across all three pillars (economic, social and environmental). The knowledge required is multifaceted both in terms of spatial and temporal extent, and in terms of the parameters, and are often highly sectorial specific. These knowledge requirements are broader than the operational requirements of the industry and extend into the information required by financial institutions, such as banks and insurers, as well as investors to ensure the industries are meeting either internal Environmental, Social, and Governance (ESG) requirements or external drivers such as the European Sustainability Taxonomy or the Task Force for Nature-related Financial Disclosures.

It is also important to recognise that the blue economy represents an unparallelled opportunity for collecting ocean observations. The industry already collects vast amounts of data that could be utilised by researchers but are often not available due to commercial sensitivities, or it may be in incompatible formats. Furthermore, the infrastructure and activity within the blue economy offers a unique platform for instrumentation, data collection and collaborative research.

8.2. Anticipated Scientific Developments by 2040

The blue economy developments up to 2040 differ significantly from other themes within the Grand Challenges. Encompassing drastically different areas of research from aquaculture to shipping and marine logistics, development can come from a wide variety of areas. The consensus across the community is maximising our capability whilst minimising our environmental impact. Outlined in this section, we discuss some of the overarching anticipated research areas that will become more prevalent by 2040.

Higher resolution monitoring and forecasting using remote sensing, such as satellite platforms, remote operating vehicles (ROVs) and *in-situ* measurements is a key area that is expected to develop, affecting all the Grand Challenges but of particular importance to the blue economy. Observing the changing climate and understanding how this could affect many of the blue economy areas is of vital importance, with examples such as: how will climate change affect the distribution/life history of marine species exploited by commercial fishers and aquaculture species, in terms of growth and diseases with a changing biological environment, including existential threats to aquaculture from algal blooms, ocean hypoxia and zooplankton (jellyfish) blooms; marine logistics and shipping and shallow seafloor infrastructure being subject to more extreme weather events, such as rogue waves and extreme storms; and coastal maintenance changing with sea-level rise and changing tidal patterns. These examples act as only a few in a long list of areas where higher resolution monitoring and forecasting is key. Advances in machine learning applications are already demonstrating weather forecasting capabilities that are outcompeting conventional techniques, allowing the amalgamation of data across different spatial and temporal scales (e.g. Atmospheric Model and Discrete Aerial Vehicle), but this work is expected to expand to include ocean modelling and coupled atmospheric-ocean modelling.

Long-term environmental understanding requires data to be collected in the right location to encompass the most effective understanding of the changing environment. These data can comprise everything from scientific experimentation for oceanographic parameters, to direct collection of environmental information about the ecosystem. The current method in marine logistics is to plan data collection ahead of time, as scientific cruises or experiments, and then update our current understanding in models, or as independent information after returning from the cruise. To collect data most effectively, scientists should aim to maximise science gain per day of operation. Anticipating changes up to 2040, we expect the marine science fleet to include more autonomous platforms, requiring planning across a much larger fleet of vehicles that must be reactive to the data being collected, updating their planning schedules to maximise the science gain whilst minimising inactive time, and subsequently carbon cost. To achieve this anticipated development, we require automated planning methods that leverage artificial intelligence that can help operational planners to quickly plan new marine vessel schedules. During data collection, the information can act to update our understanding of the changing environment, as we are already seeing with the development of digital twins, anticipated to be a key component of ocean understanding and forecasting by 2040.

8.3. Key Science Questions, Knowledge Gaps and Uncertainties

8.3.1. Fundamental Knowledge Gaps:

Future-Proofing Infrastructures Against Climate Change

- We need to further develop offshore wind and a strong blue economy as a key UK strategy. The UK has committed to an unprecedented scale of marine infrastructure building to secure renewable sources of energy, and conflicts in marine use and marine health can be avoided if new infrastructure is multi-use and complementary. UK-led marine research, building on established in-country expertise, can make that happen.
- We need research into dynamic marine spatial planning that incorporates environmental changes and sectoral impacts. For example, combining sea surface temperature data from various sources to create accurate global environmental maps. Management tools are also moving towards being species agnostic to allow consideration of habitat functionality. This needs observations with high-quality cameras.
- There is a need to develop methods to assess and understand the cumulative impacts of multiple activities (e.g. offshore wind farms, shipping routes) on marine ecosystems, to support effective environmental management and policy making.
- There is a gap in research underpinning sectoral investment in offshore carbon storage, and currently, this area is driven by the private sector. Further engagement is needed to validate research efforts, to identify and validate methods and approaches to optimise gain over expense.
- The aquaculture sector is limited to a significant extent by regulation (veterinary, environmental etc) but also lacks a focused and applied approach to tackling the industry's challenges. There are no facilities for testing new technology or approaches; rather this is conducted by the industry itself. The exploration and development of alternative production approaches, such as land-based technologies (Recirculating Aquaculture Systems) and species diversification, is not actively addressed. Future-proofing the industry will require the testing and innovation, and development of species diversification, leading to improved sustainability of the industry and food security. More scientific research is required to support these developments, along with the availability of testing infrastructure, such as research farms and facilities.

Building a Unified Blue Economy

- Uniting the currently fragmented efforts of different sectors (e.g. energy, aquaculture, shipping, tourism) to establish collaborative frameworks will help promote integrated approaches to marine research and management through sharing knowledge, data, resources, and best practices. This can be achieved through joint research initiatives, shared data platforms, and interdisciplinary working groups.
- Communicating the impacts of policy decisions, cutting-edge techniques and data to the wider, non-scientific community is essential. There is a need for more engagement and education programs that provide accessible information for the general public. This is important for highlighting the efforts to improve sustainability while future-proofing the blue economy, realising that the blue economy affects people beyond those directly

involved in it. This can help raise awareness and support for marine conservation and sustainable practices.

- Research is needed to understand the ecosystem level trade-offs between food production systems and ecosystem services. This includes evaluating how these systems can coexist sustainably, balancing food production with the preservation of coastal ecosystems.
- We need to design better fisheries practices, and this could be through the use of AUVs. The practice of scallop dredging, for instance, needs technological solutions, and we need to identify biodiversity on the seafloor without impacting seafloor integrity.

Centralising Data Storage

- There is a need to centralise data storage by bringing together private sector, research and legacy data into unified high-capacity repositories. This would enhance accessibility, integration, and utility.
- Many valuable datasets only exist in non-digital formats. Digitising this legacy data and incorporating it into modern databases will boost the available data pool and provide historical context for current and future research.

8.3.2. Sector Specific Knowledge Gaps

Offshore Energy

- Better knowledge in biodiversity baselining is needed to understand the environmental impacts of offshore energy projects. Research is needed to connect local and global environmental data to provide accurate assessments.

Aquaculture

- Understanding the impacts of environmental changes on species growth, disease, and ecosystem interactions within aquaculture is needed. To support the management of these impacts, developing ecosystem-wide models that integrate aquaculture data with broader environmental data will be needed, along with strengthened focus on developing tools for managing the biological and physical impact from both the aquaculture and ecosystem management perspectives. Low trophic level aquaculture depends strongly on good water quality and can be impacted by extreme weather events, for example. Higher trophic aquaculture is also threatened by climatic changes affecting water quality, biological events and extreme weather. These not only incur economic cost but also impact animal health and welfare.

Fisheries

- Currently, stock recruitment relies on a good understanding of biogeochemical processes. Stock collapses have led to closed fisheries. Finer scale (often inshore) processes are not known, and limit biogeochemical modelling accuracy and use. A large gap in the knowledge in models for fisheries is recruitment and its drivers.
- Taking physical samples over longer terms (decades) is key to understand the behaviour of larvae and connectivity, and to link this to Good Environmental Status. For example,

this type of sampling work is funded by Welsh Government (Natural Resources Wales, 2019).

- Understanding the impacts of BE activities on fish species and on the commercial fishing sector.

Shipping

- The potential impacts of climate change on shipping patterns needs research. This includes understanding the effects of zero-carbon shipping and changes in port infrastructure.
- There is a growing need for autonomous ships and enhanced requirements for metocean information, digital twins for operations, and routine instrumentation of vessels.

Coastal Maintenance

- Research is needed to develop accurate, long-term coastal forecasts to predict the effects of climate change, such as sea-level rise, on coastal regions. These forecasts can help in planning and implementing adaptive measures to protect coastal communities and ecosystems and infrastructure over a range of timescales.

8.4. Observation and Product Requirements

In understanding the future observations and products, it is vital to understand the essential ocean variables (EOVs), their space-time scales and accuracies. Outlined in the Global Ocean Observing System (GOOS), there is a series of EOVs that must be collected for ocean forecasts and climate projections (e.g., currents, sea level, temperature, salinity, waves, ice, and biochemical variables; Ciliberti *et al*., 2023). Throughout this section, we discuss some of these key EOVs and their dependence/connections to aspects of the blue economy.

Currently, key ocean variables (e.g. sea state, sea ice, surface currents, dissolved materials, biomass and diversity parameters) are collected from a series of different observation platforms: remote sensing satellite data, floats and drifters, and ships of opportunity, marine autonomous platforms or fixed buoys/moorings. One positive change in future observations would be an expansion of the Ships Of Opportunity Programme (SOOP; Global Ocean Observing System, 2023), where a core set of observations are mandated from all vessels, acting to reinforce measurements for these key variables. Collecting these datasets repeatedly over time allows both for the establishing of a baseline to measure change against, and a record of changes to the environment on longer timescales. Additionally, the integration of physical, chemical, geological and biological datasets enables a holistic understanding of ecosystem processes and functions, ultimately providing an understanding of the prevalence of ecosystem services, which have global implications (e.g., biogeochemical cycling, thermohaline circulation, climate regulation). Similar aspects have already been achieved in the aviation field, with all commercial passenger flights using Rolls-Royce engines having data collected and used in Met Office climate models. Data collected underway from marine vessels would allow for data at a finer resolution temporal scale (hourly) but sparse spatial coverage along vessel tracks. Beyond the data collected, future requirements would have to leverage observational data at very different spatial and temporal scales, as is already being investigated in the realm of physics and observational informed machine learning and could be leveraged by the ocean physical models.

Understanding and supplying decision support to the blue economy to minimise the effects on fragile environments is key to mitigating anthropogenic effects on wildlife. This will call for information on wildlife-aware ship routing, requiring multiannual, time-stamped location data for migratory species and those local to the area, along with historical vessel strike occurrence data; damaging effects of ship equipment, using passive acoustic monitoring in overlapping areas of high vessel and species traffic; and wind farm/aquacultural effect on local ecosystems, requiring data on biogeochemical parameters across the impacted area. A future product requirement could be the inclusion of science in policy, leading restrictions and regulations, where toolkits are supplied to marine vessel operators to check that they maintain compliance. This would require a detailed connection between EOV forecasting to the maritime sectors. One sector where this is most applicable is marine shipping, where climate change is leading to the opening of new shipping routes through the Arctic. Environmental-aware routing would allow governmental officials to minimise the detrimental effect of shipping by supplying routes that both minimise the carbon cost but also take into account the area for migrating wildlife and proximity to fragile environments (e.g. sea-ice front).

Marine logistics and management are required in order to meet net zero, with current operational planning applied only for one ship at a time, generally without the inclusion of real-time marine environmental variables. As technology develops, and our ocean marine variable forecasts increase both spatially and temporally, it allows opportunity to develop tools that can minimise our non-productive use of marine vessels globally (e.g. ship alongside) by maximising the science collected per tonne of carbon emitted. These tools will also allow for cases of a 'vessel of opportunity', where data could be collected, whilst providing another research cruise, minimising the requirement for standalone science cruises in that case.

8.5. General Description of Key Capabilities

The key capability requirements for the blue economy can be split into two categories that span both of the knowledge requirements identified in section 8.1 (those required by society and those required by the participants of the BE). The first broad category of capability requirements concerns platforms and sensors; the second is around data collection, storage, integration, interrogation, synthesis and utilisation.

8.5.1. Observational Infrastructure

In terms of the platforms and sensors, the blue economy offers unparallelled opportunities to provide a platform for ocean data collection. These data will either be collected as operational or regulatory requirements of the industrial activity, or by using the infrastructure associated with the blue economy as platforms of opportunity (in a way that is analogous to 'Ships of Opportunity'). In either case, there is a clear need for better partnership between research institutions and the blue economy sector. Recent developments in autonomous underwater vehicles (AUVs) and associated technologies have significantly enhanced the ability to collect high-resolution data in fine scale, within inshore and shelf sea environments. By integrating tools such as multibeam bathymetry, side-scan sonar, magnetometers, and advanced oceanographic sensors, shallow-water surveys can now gather detailed information from both the seabed and the water column simultaneously (Marouchos *et al.*, 2015; Woock and Frey, 2010). Compact, manoeuvrable platforms equipped with vision-based navigation and oceanographic instrumentation are especially well-suited for complex settings like estuaries, coastal zones, and inshore waters, where they effectively address challenges posed by fluctuating salinity and dynamic currents (Barrett *et al*., 2010; Fisher and Nidzieko, 2024). Coordinated operations involving AUVs and unmanned surface vehicles (USVs) support efficient, cost-effective, and long-duration surveys by ensuring continuous connectivity and enhancing mission efficiency (Busquets *et al*., 2013). These advanced systems not only support habitat mapping and biodiversity assessments but also contribute vital data for predictive coastal modelling, leading to improved accuracy in hydrodynamic and bio-optical forecasts (Ludvigsen *et al*., 2014; Specht, 2023).

8.5.2. People, Skills and Partnerships

Through the process of stakeholder engagement, it is clear that levels of engagement between the UK scientific community and the blue economy are relatively lower than in other countries, but is improving, as is evident from recent engagement events (Lancaster University, 2024; Southampton Marine and Maritime Institute, 2023) and outputs (Depellegrin *et al*., 2022), along with the more recent ECOWind, ECOFlow and INSITE programmes, and the VALMAS project. Researchers in these projects explore how marine infrastructure development can coexist with the conservation of healthy marine ecosystems and energy flow.

If the large potential of the private sector for marine data acquisition is to be realised as a driver of marine science, then greater partnership between the two sectors is needed. This partnership will require long-term investment in human resources to build relationships between those involved, and to develop the trust to allow access to data and infrastructure. In addition, the use of platforms of opportunity will require significant development of associated sensors that are compatible with operational conditions. Furthermore, if industry data is to be made available for scientific purposes, then there is a clear need to be able to access and use that data in a meaningful manner, which leads on to the second broad category of capability requirement.

8.5.3. Digital Infrastructure

To paraphrase Cliff Stoll and Frank Zappa, ‘data is not information, information is not knowledge’ and although data acquisition in the blue economy, as described above, offers huge potential, the value will only come if data can be transformed into meaningful information and knowledge (and hopefully leading to understanding and wisdom). The tools required to integrate, interrogate and interpret data were emphasized as key capabilities from the blue economy workshops and broadly fell into three groups.

1) **Internet of Things (IoT)**: The real-time acquisition of data from multiple platforms requires high levels of connectivity in the offshore space, along with the ability to store and integrate these data. This level of integration needs significant technological development for offshore, subsea, and sub-seafloor environments.

2) **Artificial Intelligence (AI)**: AI is well suited to the development of insights from large heterogenous data in close to real time and can be used to support informed decision-making for industry, regulators and researchers.

3) **Ocean Digital Twins**: Advanced modelling, reparametrized in close to real time from ocean observations, offers huge potential to predict environmental behaviour and the impacts of ocean-based activities. This can be used both for risk management and

management scenario development, along with hypothesis generation for future research areas.

Specifically, the following examples were highlighted at the workshops:

- ★ Digital information and AI could support site usage optimisation, providing wide access to data (including from competing private sectors).
- ★ AI will be vital for optimal maintenance of energy and equipment, route and logistics optimisation, better site selection and licencing, and to integrate data from multiple sectors and sources.
- ★ Long-term forecasts can provide a better understanding of coming changes with a shifting baseline.
- ★ Real-time monitoring of marine environments enables quick responses to hazardous events.
- ★ Creating a digital twin of offshore infrastructure can help the national grid forecast with changing weather conditions.

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PART 3: Synthesis and Recommendations

Chapter 9: Integrated Science Themes

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9.1. Advancing Understanding of the Broader Earth System

The UK marine research infrastructure not only provides critical data to underpin knowledge and understanding of the marine system, but also facilitates investigation of the connections and feedbacks between the ocean and other components of the wider Earth system – for example, providing a platform for crucial observations of the atmosphere, lithosphere and cryosphere in the marine domain (e.g. Heinze et al., 2019; Koppers and Coggon, 2020; Wang et al., 2023; Monteiro et al., 2025). Broader understanding of the role the ocean plays in the operation, regulation and evolution of the whole Earth system is critical to addressing the grand challenges we face. Indeed, many of the pressing and most intractable science questions can only be addressed through consideration of multiple system components. The sensitivity and resilience of components of the Earth system to climate change, especially with respect to threshold or tipping points, is an important aspect of this, particularly given the scientific uncertainties and importance in future climate risks and impacts (Wang et al., 2023).

9.1.1. The Atmosphere: Marine Meteorology, Atmospheric Composition and Air-Sea Fluxes

The Grand Challenge on the Role of the Ocean in a Changing Climate (Chapter 4) noted sustained observations in air-sea fluxes of heat, carbon and upper ocean dynamics can reduce uncertainties in climate projections. Currently, large uncertainties and the lack of measurements in remote locations – such as in the polar oceans, or during winter seasons – prevent us from accurately capturing global and regional changes in air-sea fluxes and sea level. Inaccurate data on ocean-atmosphere interactions then lead to biases in global climate and Earth system models (e.g. Heinze et al., 2019; McKay et al., 2021).

The development of fully coupled prediction systems (which might include numerical models or AI emulators) right down to weather timescales has demonstrated the importance of taking observations above and below the air-sea interface, to better understand the dynamics of air sea interactions. Such research is technologically challenging because of the microscale turbulent interactions involved – but the real-world benefits are tangible. The move to fully coupled Numerical Weather Prediction has led to significant improvements in predictions of storm tracks and intensity.

The World Meteorological Organisation's Global Atmosphere Watch[11] and, more recently development of the Global Greenhouse Gas Watch[12], has brought new momentum to the need to better understand and predict changes in the global atmosphere and its interactions with the

[11] https://community.wmo.int/en/activity-areas/gaw

[12] https://wmo.int/activities/global-greenhouse-gas-watch-g3w

ocean. Atmospheric compositions observed from research vessels can be relatively un-impacted by urban pollution. As an example, combined ocean and atmosphere carbon dioxide/carbonate chemistry observations are critical in estimating and monitoring the size of oceanic anthropogenic carbon uptake.

Other important surface ocean-atmosphere variables are measured from marine platforms including ocean surface wind stress, ocean surface heat flux and sea state and sea level. These are all Essential Ocean Variables (and Essential Climate Variables; Bojinski et al., 2014; Miloslavich et al., 2018). Atmospheric observations have also been taken by multiple other marine-based platforms beyond research vessels, including volunteer observing ships, fluxes moorings, and surface drifters. Increasingly, uncrewed surface vehicles are showing potential to collect comprehensive observations at the air sea interface. However, as emphasised in Chapter 4, there will remain a need for sustained, widespread, high-accuracy calibration and validation measurements mainly from research vessels.

9.1.2. Evolution of the Oceanic Lithosphere

The oceanic lithosphere is a rigid layer of rock that makes up oceanic tectonic plates (Koppers and Coggon, 2020; Figure 9.1). It is the solid Earth part of the ocean system, consisting of the seabed, layers of sediment, the igneous oceanic crust and lithospheric mantle (Koppers and Coggon, 2020). Forming at mid-ocean ridges, the lithosphere evolves as it ages and is destroyed at subduction zones. It is entirely replaced every ~200 million years resulting in the largest-scale cycle of energy and matter on the planet, which buffers Earth's environmental conditions and makes its surface habitable over long timescales, provides critical economic resources, holds one of Earth's best records of past climate conditions and provides a window into processes operating deep within the Earth (Koppers and Coggon, 2020). The system is studied by a range of direct methods, such as coring, dredging, mapping, and sampling using remotely operated vehicles, submersibles, and scientific ocean drilling and indirect methods such as passive and active-source seismic imaging. UK ship-based science has generated world-leading research using all these approaches (e.g. Rogers et al., 2012; Kirkham et al., 2025; Lai et al., 2025; Martin et al., 2025). Below are examples of topics at the forefront of solid Earth marine research, selected for their societal relevance.

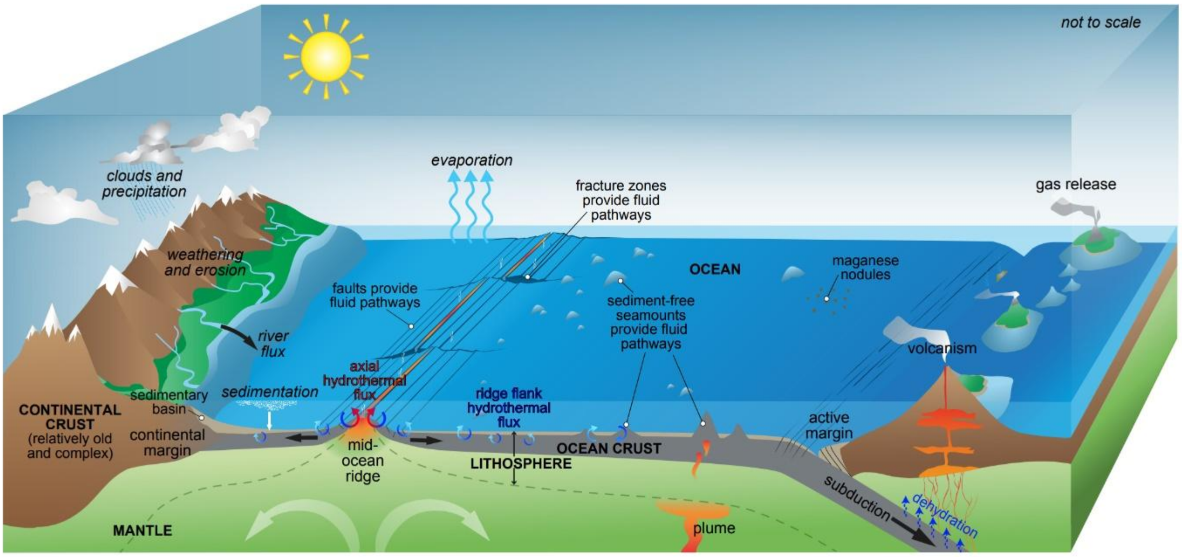

Figure 9.1: Schematic cartoon illustrating some of the interactions between the evolving oceanic lithosphere and Earth's ocean, atmosphere, biosphere, climate system, continents and deep interior (not to scale) - original figure by Rosalind Coggon, adapted from figures in Koppers and Coggon (Eds; 2020).

A Window into Earth's Deep Interior

The oceanic lithosphere plays a key role linking the Earth's deep interior with its surface. For example, heat that has been produced by radioactive decay in our planet's interior, or that is remaining from Earth's formation, is released to the surface across the seafloor. Yet, many open questions remain about the thermal state of our planet and its ongoing internal cooling (e.g. Richards et al., 2020). For instance, it is not clear which processes supply heat beneath older parts of oceanic plates (Richards et al., 2020). Mantle processes that lead to the formation of topographic structures such as seamount chains and clusters remain controversial, even in well-studied regions such as the North Atlantic (e.g. Merle et al., 2018, 2019). Further, current thermodynamical and cooling models do not reproduce many observational datasets (e.g., heat flow, dynamic topography, gravity and seismic observations) and so there are many ongoing efforts to better map and understand the dynamics of mantle convection (Richards et al., 2020).

A better comprehension of the internal structure of oceanic plates and of the transition from the rigid plate to the weaker mantle beneath is key to understanding the driving forces of plate tectonics and of associated natural hazards, such as offshore earthquakes and tsunami generation. As outlined in the Chapter 7, assessment of such hazards becomes ever more critical as population density increases in coastal regions.

Continental Margin Resources

Continental margins lie adjacent to large coastal populations and are the most exploited part of the marine system. They form when continental lithosphere is stretched beyond its breaking point as a result of distant tectonic and/or underlying magmatic forces, and ruptures into separate, diverging land masses, leading to plate spreading and the generation of oceanic lithosphere (e.g. Lavecchia et al., 2017; Koptev et al., 2018). Fundamental questions as to why this stretching occurs, and the involvement of deep mantle plumes, for example, remain unanswered (Koptev et al., 2018). Their formation is associated with significant subsidence that forms the deepest sediment accumulations on the planet. These were a major source of hydrocarbons and are likely to be key players in the search for base metals and rare-earth elements needed for the green economy transition (e.g. Petersen et al., 2016). Continental margins are hugely variable in terms of their structural architecture, which directly affects the opportunities they offer for societal use. For example, many margins host serpentinised mantle peridotites, which were exposed to seawater during extension. Such bodies, together with saline reservoirs, may be targets for the sequestration of CO_2, an emerging opportunity for mitigating anthropogenic climate change. Serpentinisation is also one of the processes that can generate hydrogen, a poorly understood geological resource that may provide a low-carbon fuel (e.g. Yedinak, 2022; Ellis and Gelman, 2024).

Lithospheric Evolution

The oceanic crust is a highly permeable aquifer through which seawater-derived fluids circulate, driven by heat released from the underlying cooling ocean lithosphere (Elderfield and Schultz, 1996; Schultz and Elderfield, 1997; German et al., 2016). The ocean basins are not therefore just an inert container for seawater – rather, they are an integral part of the ocean system. It is estimated that the entire volume of the ocean circulates through the solid Earth every ~100-650 ka with entrainment in vent plumes leading to ocean residence times of 1,000 – 10,000 years (German et al., 2016). Hydrothermal circulation occurs throughout the life of the oceanic lithosphere and drives the chemical evolution of our atmosphere and ocean (e.g. Elderfield and Schultze, 2016; Schultz and Elderfield, 1997), controls the physical and chemical conditions that allow life to develop and evolve (Koppers and Coggan, 2020), is an important contributor to iron-stimulated primary production (especially in the Southern Ocean, e.g., Tagliabue and Resing, 2016; Schine et al., 2021; Tagliabue et al., 2022), and regulates recovery from major perturbations in Earth's climate.

The nature of hydrothermal circulation and associated processes changes as the lithosphere ages and heat flow subsides. High-temperature (up to >400 °C) "black smoker" hydrothermal vents along mid-ocean ridges are the most obvious manifestation of such thermally driven fluid circulation (Baker, 2017), but we know that hydrothermal fluid fluxes through the maturing ridge flanks are many orders of magnitude more voluminous (German, 2016). Conductive heat flow deficits indicate that fluid circulation diminishes as the crust ages, but it persists through oceanic crust as old as 65 million years at temperatures much less than 100°C (Kardell et al., 2019). However, the resultant chemical fluxes between the aging crust and the ocean, and when and how this threshold from advective to purely conductive heat loss is crossed remain uncertain.

Volcanic Emissions and Carbon Cycling

Significant volumes of volatiles are released to the ocean and atmosphere by submarine and associated volcanism (e.g. Le Cloarec and Marty 1991; Wallace, 2005). At subduction zones, where the hydrated oceanic lithosphere is returned to the deep Earth, temperature and pressure regulated dehydration reactions release fluids from the down going slab (Wallace, 2005). These fluids may be expelled directly, such as in forearc mud volcanoes, or may cause melting in the over-riding plate. This melting forms arc volcanoes which often erupt violently and threaten civilian infrastructure, such as the eruptions in Montserrat in 1995 and Tonga in 2022 (e.g. Sheldrake et al., 2017; Lindsay and Robertson, 2018; Maneela and Kumar, 2022; Terry et al., 2022). Similarly, within-plate hot-spot magmatism from deep mantle sources, generating volcanism such as that in Hawaii or on La Palma, may also pose significant threats, as does the plume-augmented mid-ocean ridge setting of Iceland (Tweed, 2019). Much work is needed to better understand the eruptive behaviour of these systems and to manage their associated hazards, with the records of such events often only accessible on the seabed and via ship-based research (Sheldrake et al., 2017; Lindsay and Robertson, 2018).

The oceanic crust and upper mantle are significant carbon reservoirs (Müller and Dutkiewicz, 2019). The amount of carbon stored within them is poorly understood because of uncertainties in the extent and duration of hydrothermal calcium carbonate precipitation in oceanic crust, the global role of ultramafic rock serpentinization in CO_2 uptake, and the utilization of the various forms of carbon compounds by microbial communities beneath the seafloor (Müller and Dutkiewicz, 2019). The fate of carbon stored in mature oceanic lithosphere during subduction is also unknown because carbon may be transferred along volatile pathways that are currently poorly quantified (Plank and Manning, 2019). For example, we do not know what proportion of the crustal carbon budget is recycled into the mantle, degassed back to the atmosphere via arc volcanism or otherwise returned to the surface via fluid flow in the forearc.

Chemosynthetic Communities

The discovery of megafauna reliant on microbial chemosynthetic production at high-temperature deep-sea hydrothermal vents demonstrated that communities of organisms could live independently from sunlight and at higher temperatures than previously realised with implications for our understanding of where life could occur elsewhere in the universe (e.g. Baker et al., 2010; Longo and Damer, 2020). Lower temperature vents driven by serpentinization at the Lost City vent site on the mid-Atlantic Ridge present conditions that may be like those which gave rise to life on Earth 4 billion years ago (e.g. Martin et al., 2008). The extreme conditions found in such ecosystems have driven the genomes of vent-endemic organisms to evolve adaptations to high temperatures and pressures, low oxygen availability and the presence of toxic chemicals. As such they are of interests to biotechnologists for enzymes for use in science and industrial applications, as well as inspiration for materials (e.g. the scales of the scaly-foot snail from Indian Ocean vents leading to discovery of new photovoltaic materials; Yamashita et al., 2023). The biological communities of vents and other chemosynthetic ecosystems such as hydrocarbon seeps and food falls (e.g. whale carcasses and wood) comprise a high proportion of endemic species and are useful in understanding species distribution, population connectivity and the factors driving community assembly in the deep sea (e.g. Sibuet and Olu, 1998; Tunnicliffe et al., 2003; Wolff, 2005). Given the potential for mining of seabed massive sulphides at vents, knowledge of population connectivity and dynamics is important in the management of mineral exploitation and conservation of endemic chemosynthetic species with small geographic ranges (e.g. Vrijenhoek, 2010).

The Deep Biosphere

The deep biosphere remains a large and poorly known carbon reservoir. It is likely one of the largest ecosystems on Earth, yet its size, activity, and connectivity are poorly understood, as is its influence on global biogeochemical cycles (Parkes et al., 2014; Colman et al., 2017). The deep biosphere plays a critical role in chemical exchanges between the surface and deep sub-surface worlds (D'Hondt et al., 2019). It also plays an important role in balancing the oxidation-reduction conditions on Earth principally through mediating the burial of organic matter and the removing reduced material from the ocean (D'Hondt et al., 2019). Deep subseafloor microbial cells principally fix carbon and nitrogen, but through volcanic and other processes they also cycle other volatiles such as sulphur, leading to the accumulation of massive sulphide deposits. Oxidation can also be controlled by sub-seafloor microbial action, causing significant pyrite formation on continental slopes during glacial low stands and extensive redox reactions within basaltic crust. The generation of pyrite through sulphate reduction in sediments is the main cause of loss of sulphur from the ocean as well as a principal source of alkalinity (D'Hondt et al., 2019). Nitrate reduction in sediments also reduces the amount of nitrogen available in the ocean for primary production (D'Hondt et al., 2019). Finally, deep biosphere microorganisms also create or destroy subsurface resources such as hydrocarbons, phosphates, dolomites and barite (D'Hondt et al., 2019). These processes which likely vary in significance in different oceanic tectonic settings, provide crucial, bioavailable elements for life and stimulate us to gain a fuller understanding of microbial-driven cycles in the subseafloor environments.

Critical Metal Deposits

Fluid flow facilitates the cycling of metals between the lithosphere and ocean. Over millions of years, this cycling can lead to the formation of massive sulphides and ferromanganese nodules on the seafloor (Petersen et al., 2016). Hydrothermal activity along mid-ocean ridges, back-arc ridges and other submarine volcanoes concentrates key metals in subseafloor ore deposits and provides useful analogues for understanding ancient deposits exposed on land that are important sources of traditional metals (Cu, Zn, Au) and critical metals (Co, Cr, V) used in green and advanced technologies (Petersen et al., 2016). There is currently a poor understanding of why subseafloor fluid flow leads to the accumulation of potentially economic metal resources at other locations, while elsewhere no deposits form and instead seawater has increased dissolved elemental concentrations (Petersen et al., 2016). Better understanding will reduce exploration risk of the critical materials needed for the energy-transition in the future.

9.1.3. The Coastal Interface

As outlined in section 5.2.2, shelf seas connect the open ocean to the coast through cross-shelf exchange processes (e.g. Brink, 2016) that are regions of great change and are subjected to a range of environmental and human pressures (e.g. Doney, 2010; Halpern et al., 2019; He and Silliman, 2019). There are also often gaps in observational capability, largely because sensor technologies for data acquisition in biogeochemistry and biology have lagged behind those for physical oceanography, although this is changing (Brink, 2016), and environmental monitoring is focused on the coastal environments. Connecting observation and predictive capabilities across the shelf presents many opportunities for understanding and predicting both open ocean and coastal environments.

The Grand Challenge on the Role of the Ocean in a Changing Climate (Chapter 4) highlighted the importance of more real-time observations at the scales required for high-resolution modelling in the transition zones between continental shelves and open ocean, which are essential for weather forecasts and for studying the biogeochemistry and productivity of shelf seas (e.g. Brink, 2016). For the Grand Challenge on Hazards and Extreme Events (Chapter 7) reduction in coastal resilience including the increased frequency and impact of hazards and biodiversity loss was identified as a critical issue. As a result, the need for high resolution spatial and temporal mapping of the seafloor in the coastal zone as well as measurement of coastal waves, tides and surges, were identified. These represent significant cross-over to increased hazard risk from a changing climate. The need for high-resolution monitoring and forecasting is also expressed in the Grand Challenge on the Blue Economy (Chapter 8) especially in the context of coastal regions for long-term planning for adaptation to climate change for ecosystems, infrastructure and coastal communities (e.g. Rayner et al., 2019; Bax et al., 2022). Given the intensity of human activities in the coastal zone it is also a priority area in the Grand Challenge on Biodiversity and Ocean Health (Chapter 5) (e.g. Rayner et al., 2019; Bax et al., 2022). Habitat mapping is identified as critical for managing human activities impacting on biodiversity through marine spatial planning with the latter also being identified as a critical need for the coastal blue economy (Bax et al., 2022). The importance of spatial conservation tools, such as marine protected areas, for maintenance of ocean health in coastal areas also requires information on ecosystem and population connectivity (see below).

9.1.4. Interactions with Ice Shelves and Sea Ice Dynamics

Some of the greatest changes in the ocean and cryosphere are being witnessed in the polar oceans. The Grand Challenge on The Role of the Ocean in a Changing Climate (Chapter 4) highlights these changes – including mass loss from ice sheets and glaciers, loss of sea ice and increased permafrost melt – and the resultant change in freshwater discharge which are altering ocean circulation and contributing to major changes in sea level. Indeed, uncertainties around the cryosphere changes including the role of the ocean in contributing to ice melt, is a major contributor to uncertainties in sea level projections (e.g. Kopp et al., 2023). The Grand Challenge on The Role of the Ocean in a Changing Climate (Chapter 4) highlights that understanding the effects of rapidly changing polar regions on global climate remains a key research priority (e.g. Goosse et al., 2018; Post et al., 2019). As indicated in Chapter 5, changes in ice coverage and sea ice dynamics also have major consequences for polar ecosystems (e.g. Rogers et al., 2020). At the poles, sea ice is a major habitat for many aquatic predators and also, in the Southern Ocean, critical for the completion of the life cycle of krill (*Euphausia antarctica*), a keystone species (e.g. Rogers et al., 2020). The highly endemic Antarctic biodiversity is unique and has evolved to live at constant low temperatures over millennia (Rogers, 2007, 2012). It is therefore highly vulnerable to changes in temperature and other physical conditions. A key gap in observational capability is under the ice, due to the hostility and inaccessibility of the environment, and challenges communicating with deployed equipment under the ice.

9.1.5. Multiple Stressors and Intersecting Drivers of Change

Many of the synergies between Grand Challenge issues are discussed in the Grand Challenge chapters, highlighting in particular that each challenge can rarely be considered in isolation. For example, understanding changes in a particular coastal ecosystem means unpacking the pressures resulting from overexploitation of biotic and abiotic resources, climate change (e.g. heat, acidification), pollution, shipping, coastal development, as well as natural hazards and extreme events, leading to habitat destruction and loss of biodiversity (e.g. cumulative human impacts, Halpern et al., 2019).

One intersection in particular stands out: the impact of climate change on all the Grand Challenges. Climate Change provides the additional challenge of a shifting baseline while trying to understand complex ocean processes, feedbacks, and how it amplifies other pressures (e.g. He and Silliman, 2019; Gissi et al., 2021). Climate models will be increasingly needed to determine thresholds and feedbacks such as the relationship between ocean warming and changes in deep ocean circulation.

For Natural Hazards, climate change will affect the frequency, magnitude, nature and location of hazards (e.g. Spalding et al., 2014; Ghorai and Sen, 2015; Laino and Iglesias, 2023). Understanding of these intersections and where impacts will be felt into the future is needed to guide efforts in enhancing resilience. Improved predictions of hazards and extreme events will be key, requiring greater understanding of the underlying processes which govern events. Conversely, the feedbacks between some natural hazards and climate change, e.g. volcanic eruptions impact on atmospheric conditions, seafloor release of greenhouse gases, carbon transport by turbidity currents, are important factors to consider and will need to be better understood to improve our understanding of climate change mechanisms.

With a growing blue economy (Chapter 8), there is an increased reliance on coastal and offshore industries. Understanding the environmental conditions their structures need to withstand, and where to build, e.g., offshore windfarms, with future changes in mind, will be critical for future proofing industries. Changing environmental conditions will also impact the planning, location and active management of other blue economy areas such as aquaculture, fisheries, coastal infrastructure, and shipping.

For Biodiversity and Ocean Health (Chapter 5), climate change is impacting the sensitivities, thresholds, and resilience of ecosystems to changes. Sensitivities to changes are likely to be higher, with resilience likely to be lower and thresholds to change likely to be reached more frequently. For instance, a coral reef already under stress as a result of fishing and coastal pollution will be more vulnerable to climate change impacts such as mass coral bleaching and less able to recover (e.g. Suggett and Smith, 2019; Donovan et al 2021). Marine species are migrating polewards as a result of ocean warming and so baseline distributions of species are changing, and communities of species reconfiguring (e.g. Burrows et al., 2014; Poloczanska et al., 2016; Hastings et al., 2020). Connectivity, in terms of source and sink populations, and habitat availability, also come into play as ecosystems shift and are remodelled (e.g. Burrows et al., 2014) with significant implications for conservation of species and ecosystem service provision for society.

For the Pollution issues (Chapter 6), there is strong cross over with the Natural Hazards and Extreme Events Grand Challenge (Chapter 7) as, for instance, extreme events can cause pollution (e.g. remobilisation of pollutants buried in sediments or mobilisation of plastics; Crawford et al., 2022). Harmful algal blooms (HABs) could be considered both a natural hazard and a form of 'pollution' event and their occurrence is rising, both as a result of climate change and increases in other forms of pollution, especially eutrophication arising from human nutrient input (e.g. Gobler, 2020; Griffith and Gobler, 2020). HABs also act as a climate change co-stressor, interacting with climate change effects and driving unpredictable and poorly studied impacts on ecosystems (Griffith and Gobler, 2020). Climate Change effects will also alter the chemistry of pollutants as well as potentially lower toxicity thresholds as a result of climate-induced stress on organisms (Cabral et al., 2019; Kibria et al., 2021). Pollutant pathways in the ocean may also be altered by changes in circulation and stratification. As the impacts of climate change become increasingly severe, human efforts to mitigate climate change through geoengineering schemes, such as through marine carbon dioxide removal, may also lead to pollution as well as other unforeseen effects on ecosystems (e.g. Levin et al., 2023). Ship pollution around sea-ice (changing the colour and therefore the albedo effect of ice) has direct feedback to climate change (e.g. Browse et al 2013; Li et al 2021).

The unequivocal evidence that Earth's climate is changing underlines the importance of not only monitoring the nature, rate and magnitude of its changes, but also deepening our understanding of the underlying processes that govern the impacts and manifestation of those changes in other components of the Earth system and its ecosystems, alongside developing and testing this understanding using paleorecords. It also presents challenges in the design of multidisciplinary programmes to observe tipping points and non-linear responses at a range of scales, from individual organisms to whole ecosystems. The intersection of multiple stressors in the ocean will be an important topic of research, challenging our ability to capture key processes by observing and modelling the range of variables and scales required, while also challenging our digital infrastructure to integrate, manipulate, and interrogate complex and diverse data (section 8.4).

9.2. Observational and Process Scales

The challenge of measuring properties and processes over the full range of required spatial and temporal scales is a common theme throughout all of the Grand Challenges and thus has key implications for capability requirements.

The NZOC Work Package 1 Report highlighted that '*capturing the range of spatial and temporal scales relevant for understanding oceanic processes is – and will continue to be – a key challenge in marine science.'*

The need to capture the underlying processes which govern how changes manifest also transcends all Grand Challenges (see e.g. Sections 4.4, 7.3). Understanding the interactions between components of the Earth system and unpicking the multiple drivers of changes in the marine and other system components requires a mechanistic understanding of feedbacks, which will be essential for improving predictive capability. For example, in Chapter 4, it was noted that uncertainties remain in the drivers and future evolution of the mixed layer depth and stratification under a changing climate, which has implications for the sequestration of anthropogenic heat and carbon, and biological productivity. Improved understanding of the underlying processes which govern such large-scale structural changes is essential to improving how we predict future change.

An international example is the TPOS 2020 project, which reflected the challenge of trying to understand ocean variability against the background of a shifting baseline as a result of continuing climate change, which was increasing the variability in how the El Niño-Southern Oscillation (ENSO) manifested. There is recognition that rather than measure how we understand ENSO to manifest, we should measure the underlying processes which govern *how* an El Niño manifests. This shift in emphasis was seen to be key to improving predictions of ENSO and focusing observational strategy where the observations could have most impact on improving predictability.

This is consistent with the findings from the NZOC Work Package 1 Report which highlighted: *'there is a need to move from broad correlations to understanding connections, processes, and mechanisms in order to have greater predictive power and confidence'*. Such requirements challenge our future capability and indicate how a dynamic approach to the integration of observations and models will be required to advance understanding – of mechanisms, thresholds and feedback loops – and enhance prediction of the changing ocean and broader planetary system.

Key areas for development highlighted through Grand Challenge discussions relevant to observational scales and processes included:

- Shifts in boundaries, ranges and scales present challenges for observing strategies but also opportunities to consider dynamic/smart/responsive observation and prediction strategies.
- Fluxes and feedbacks at interfaces and the role of turbulent mixing: the nature of communication between atmosphere and surface ocean and on down through the

thermocline, water column and seafloor and implications for measuring temporal changes in biology (where currently still reliant on periodic physical sampling).

- Resolving biological and chemical processes affecting biogeochemical fluxes.
- Understanding the role of biodiversity in ecosystem functioning and services to society.
- Measuring states verses rates – including measuring rates and gradients over small scales.
- Targeting data collection in areas of most uncertainty, and/or areas changing rapidly in space/time.
- Requirement for full ocean-depth observations and in areas of major gaps (e.g. under ice).
- Understanding fine scale ocean processes and improving representation in models.

9.3. The Marine System: Multidisciplinary System Science

There is a growing trend towards the development of truly interdisciplinary programmes (section 2.3) which will likely continue and increasingly require truly transdisciplinary approaches to address the critical scientific and societal challenges being faced. This challenges both our observational and digital technologies, not just in terms of expanding capability for measuring a growing range of coincident variables at comparable spatial and temporal scales but also managing and interrogating diverse data and hence improving the pipeline from data generation through to knowledge as required to understanding complex processes and feedback loops.

The uptake, fate and storage of carbon in the ocean as part of the wider global carbon cycle is an example of how interactions among physical, chemical and biological processes in the ocean and interactions with other key planetary components (e.g. atmosphere and lithosphere) over different temporal and spatial scales, determine whole system behaviour (e.g. DeVries, 2022). The complexity and multi-scale characteristics of such interactions thus provide particular challenges for observation and prediction. In addition, given the growing interest in the potential for marine carbon dioxide removal (mCDR), there is an increasing need to understand the processes that govern carbon uptake and storage in the ocean and how they might be changing, as well as the potential need for evaluating the efficacy of mCDR and both intended and unintended impacts on biogeochemistry, ecosystem processes and biodiversity (e.g. Levin et al., 2023). Evaluation and monitoring of pilot projects and their ability to scale against the background of an ocean where capacity to uptake carbon and respond to other environmental pressures is changing, will be required (e.g. see Doney et al., 2025). Ultimately, a greater understanding of the mechanisms that govern ocean carbon uptake, feedback and storage will be required to improve predictions of future climate.

It is already well understood that the uptake of anthropogenic carbon is predominantly a physically driven process, linked to the carbonate chemistry and physical processes, including the formation of mode and intermediate waters (e.g. Levy et al., 2013; Ludicone et al., 2016). However, there are mechanistic aspects, including small-scale biophysical interactions and mixing processes, which still require characterising (e.g. Bergkvist et al., 2018). The interplay between ocean carbon and oxygen chemistry needs to be considered, particularly changes in stratification affecting carbon uptake along with the expansion of Oxygen Minimum Zones

(OMZs) impacting the balance between photosynthesis and respiration in the ocean, as well as links to the production of other climate active gases such as N_2O (e.g. Kalvelage et al., 2013).

The role of biological processes in ocean carbon uptake has recently been the focus of a number of UK and internationally led programmes (e.g. PICOLO, BIO-Carbon, BIOPOLE (UK), APERO (France), NASA EXPORTS (USA), Transforming Climate Action (Canada), SOLACE (Australia)). Because of the range of processes acting over multiple time and space scales which interact to determine the biological uptake and storage of carbon within the ocean, such programmes challenge our research in terms of our ability to measure coincident physics, chemistry and biology observations at a range of scales, and model complex physical, chemical and biological processes and their interactions (see section 5.3 for more details). Indeed, although the details of these and other similar programmes vary, all are characterised by their interdisciplinarity which, from an observational perspective, often translates to multi-platform (e.g. satellite, floats, gliders, large AUVs, multiple vessels), enabling extended and/or repeated observations of the system(s) of study. Arguably, even these programmes do not yet encompass the full range of ecosystem and physical scales, for example, including the flux of carbon from microbes to the highest trophic levels and observational timescales which allow direct investigation of how changes in ocean heat, circulation and acidification are interacting to change functional groups and carbon flow. As outlined elsewhere (e.g. Section 4.5.2), there are multiple similar examples of multi state-of-the-art technologies and platforms applied to key discovery science or more applied problems in ocean physics or geoscience. Although the majority of these programmes do not yet span across into transdisciplinarity, this remains a clear direction of travel.

9.4. Ecosystem Connectivity

The ocean is an open system and as a result, its ecosystems are highly connected in three dimensions. Connectivity can be defined as the flow of materials, energy, organisms and their genes across space (Beger et al., 2022). Connectivity is highly dynamic and the spatial-temporal flows of energy, materials, organisms etc., can vary with their physical or ecological processes, the properties of the environment and of the flowing entity (Beger et al., 2022). Flows can occur in the ocean, atmosphere or seafloor/subseafloor and can vary across scales from millimetres to across ocean basins, continents and hemispheres as well as times from milliseconds to multidecadal variations (Beger et al., 2022). Ecosystems are also connected across jurisdictional boundaries, complicating the management of the ocean based on the UN Convention on the Law of the Sea (UNCLOS; Popova et al., 2019).

Connectivity has been defined in many ways but there are two principal forms: Structural and functional (Beger et al., 2022). Structural connectivity is formed by the habitat, physical features or processes which provide a framework for the movement of entities such as organisms, pollutants or nutrients (Beger et al., 2022). It might include linear connectivity, the joining or interaction of ecosystem structures from one point to another (e.g. a unidirectional flow of current from one point to another). It might include circular connectivity, a constant circular flow within or between ecosystems (e.g. an ocean gyre). Other examples include vortex connectivity, which is mediated by mesoscale eddies and vertical connectivity, between the ocean surface and seafloor or from the deep-sea to the surface in the case of upwelling.

Functional connectivity is the effective movement of an entity across a structurally connected ecosystem or ecosystems. Functional connectivity can include processes that maintain populations of marine organisms such as adult migration or larval dispersal. It can also include diffusion and mixing, such as in the exchange of gases between the atmosphere and the ocean. It can also include a wide range of ecological interactions such as grazing, predation, and competition as well as longer term processes such as gene flow (e.g. Beger et al., 2022).

Connectivity can also include spatial and temporal ranges between constrained or unconstrained (Beger et al., 2022). The types of connectivity outlined above can be subdivided into many specific cases in specific settings (e.g. Beger et al., 2022).

Understanding connectivity is fundamental to the Grand Challenges laid out in Chapters 4 – 9. For example, in the context of the climate system, structural and functional linkages between components of ecosystems are fundamental to understanding the non-linear dynamics of responses to climate change leading to potential tipping points. In biodiversity and ecosystem health, ecological connectivity is paramount when trying to understand the dynamics and persistence of populations of marine species faced with a changing environment. It is therefore key to management of human activities which impact biodiversity as well as the design of spatial conservation measures for conservation purposes. The impact of pollutants is directly connected to the way they travel through the environment – this may change as a result of global drivers such as ocean warming or acidification or localised impacts such as resource extraction, the presence of other pollutants or habitat destruction. Changes in the frequency and severity of ocean hazards reflect multiple, linked parameters such as sea level rise, changes in the frequency of extreme weather events, loss of coastal ecosystems and the development of coastal infrastructure including residential buildings. For development of the blue economy, marine spatial planning requires understanding of a wide range of connected and interacting agents from climate change to distribution of biodiversity, and economic and societal needs.

Understanding connectivity and its implications requires a holistic approach to ocean science and again often demands inter/transdisciplinary studies involving scientists and other experts. It is not possible, for example, to understand the potential persistence of populations of marine species or entire communities when faced with the challenges of a changing environment without understanding the multiple levels of connectivity within and across ecosystems. Likewise, it is impossible to understand biogeochemical fluxes without studying the full range of physical and biological processes which influence them.

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Chapter 10: Synthesis of Requirements

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10.1. Synthesis of Requirements Across the Grand Challenges

The Grand Challenges in ocean science are described in Chapters 4 to 8 (Chapter 4: The Role of the Ocean in a Changing Climate; Chapter 5: Protecting Biodiversity and Ocean Health; Chapter 6: Marine Pollution: Its Sources, Distribution and Solutions; Chapter 7: Strengthening Resilience to Natural Multi-Hazards and Extreme Events; Chapter 8: Sustainable Blue Economy and Ecosystem Services). These emphasise different areas of research or applications of data but also demonstrate many intersecting requirements in terms of the types of observations needed and the platforms from which they can be made. Between now and 2040, multiple areas of technological development, that are already in progress, will have a significant impact on all of these areas. These include development of sensors, autonomous platforms, advances in analytical capabilities (e.g. various molecular or mass spectrometry tools), remote sensing capabilities and, most notably, digital technologies, including the storage of a wider range of datasets, often at higher resolution than at the present (i.e. more observations), with greater accessibility and integrated with more advanced models and machine learning/AI approaches capable of assimilating data and producing information products in near real time for short to long-term forecasting.

In the sections below, we review the science requirements of each Grand Challenge and emphasise where these requirements are shared. These most often relate to the increasing multi-/inter-disciplinary nature of ocean and broader Earth system science for society. Understanding the societal outcomes of multilayered challenges which, with the exception of some natural hazards, are often driven by human activities, requires data from a range of scientific disciplines including not only physical oceanography, climatology, biogeochemistry, biology and geology, but also input from social sciences, economics, industrial development and policy. As stated in the Grand Challenge for Hazards and environmental extremes, over the coming decades, science must move from defining the problems faced by humanity to providing solutions whether in the form of mitigation or adaptation. This will require integration of knowledge across all the Grand Challenges reviewed by the authors of this chapter and other broader and emerging issues.

10.2. Marine Science in 2040 - Requirements

10.2.1. Climate

Variables

In addition to the internationally recognised ocean EOVs (see below), several other key state and rate measurements were outlined as being required for addressing the science questions outlined in Chapter 4. Measurement technologies for many of the required physical characteristics are well developed, although there remain significant challenges in achieving measurements across the full required range of scales (see below) with, for example, fine and microscale structures associated with mixing being one example. Biogeochemical measurements remain more diverse in nature and in some cases, more challenging. Additional state variables include trace metal concentrations and bioavailability (productivity drivers), particle size characterisation (key to ecosystems and the biological carbon pump), and inherent and apparent optical properties which control light penetration and provide global-scale proxies for biomass, community structure and productivity from both satellite remote sensing, ships and increasingly arrays of robotic platforms. Key rate variables include biological uptake/production of key elements and organic and inorganic compounds listed as EOVs (e.g. O_2, organic carbon, calcification, nitrogen fixation, biogenic silica production), remineralisation rates (of carbon and other elements and compounds), ingestion/grazing, egestion/faecal pellet production, biological growth, and physical fluxes of key EOVs, including active fluxes, sinking fluxes, and mixing and advective fluxes. Key experimental variables include maximum rates (growth, feeding, etc.), minimum rates (e.g. baseline respiration), and dependence of rates on key EOVs (e.g., temperature, O_2, nutrients, light, particle concentration). Finally, continued collection of paleo-oceanographic proxies is critical to estimate key EOVs and rates from the past and their connection with past climate fluctuations.

Spatial and Temporal Scales of Measurement

As outlined in Chapter 4 and elsewhere throughout the other Grand Challenge chapters, there is an over-arching need for scalability and flexibility in observable spatiotemporal scales. A complete infrastructure should facilitate simultaneous measurement of the ocean at scales ranging from microscopic to global, sub-second to multi-decadal, as appropriate to the specifics of the processes being studied (see e.g. Sections 4.42 & 7.3; Figs. 4.2 & 7.3). Paleo proxies must allow estimates of past ocean states and processes over centuries to hundreds of millions of years. For sustained observations in support of climate science, year-round multi-decadal timeseries are often critical. Global, continuous coverage of as many climate-linked variables as possible is a key priority. Areas of particular challenge and importance include regions with sea ice and harsh winter conditions, the water column, including mesopelagic and bathypelagic depths, the air-sea interface, the seafloor sediment-water interface, and open ocean pelagic to shelf and coastal interfaces. For targeted, experimental observations, in addition to having the capability of measuring a range of physical and temporal scales from mesoscale to microscale, it is often required that complex, interdisciplinary studies can be mounted in order to allow measurement of multiple components of the system and the interactions between them.

Accuracy

Generically, accuracy requirements for any given variable, or broader observable characteristic, are highly dependent on the science question they are used for. Detection of climate-driven changes requires accuracy to be better than the magnitude of the long-term trend, or in the worst case, a bias that is consistent over time. It is important to consider ground-truthing and cross calibration of measurements, for example, between the highest quality ship-board measurements and those undertaken using autonomous and/or remote sensing platforms. Cross-calibration is particularly important as part of the process for development and adoption of new technologies, so that data generated are comparable to past data collection. Calibration of old measurements (e.g. temperature from ships) is also critically important in the analysis of past climate change (centuries timescales).

Data integration

As throughout the Grand Challenge chapters, it was recognised that a robust and adaptive digital infrastructure will be required to enable the required advances. National and international processes and systems are already in place which allow for data to be findable, accessible, inter-comparable/operable and reusable (FAIR), but such systems are not currently generic and searchability could be improved in places. Products which leverage advanced digital tools (including ML and AI) to address this challenge could be envisaged and have the potential to add value to already available data holdings. ML and AI tools will also be developed to enable more complete synthesis of diverse data sets, while the development and use of a diverse set of numerical models will remain essential.

10.2.2. Biodiversity

Describing Biodiversity Baselines and Monitoring Change

It is estimated that between 10 – 25% of metazoan species have been described from the ocean, (Rogers et al., 2023) meaning that a large proportion of biodiversity remains undescribed, especially from less studied remote areas such as the deep sea (e.g. Rabone et al., 2023). There is therefore an underlying and continued need for basic taxonomic research for many parts of the ocean. Establishment of baselines of biodiversity including species composition, abundance, and biomass across the full-size spectrum of organisms from microbial through meiofaunal, macrofaunal and megafaunal size classes is an important, although rarely achieved, objective for biodiversity research. The precise living components of ecosystems surveyed therefore depends on the scientific and/or management questions being addressed and are often limited by taxonomic expertise available for species identification. Baselines need to be established before variations in biodiversity, in response to climate-induced or other changes to the environment (at all trophic levels), can be monitored. Such observations should encompass existing Essential Biodiversity Variables (EBVs), as well as emerging EBV markers currently being developed to maximise the information provided by eDNA and 'omics sampling.

Specific science requirements for understanding marine biodiversity and ocean health include both biodiversity-specific observations and sampling, as well as the collection of environmental data, to understand the physical and biogeochemical drivers of distribution. The most basic requirement for biodiversity research is surveys to identify and quantify species (even if only semi-quantitative or based on absence-presence criteria). These surveys can be undertaken in a range of marine habitats (coastal to mid-ocean; surface to deep ocean; pelagic to benthic; polar). Surveys are particularly important in under-sampled but economically and/or ecologically significant regions. Existing long-running ecological time series must be maintained to provide crucial (but rare) data collections spanning climate change relevant time scales (e.g. > 30-60 years). Note that sampling technologies and the platforms they are deployed from vary considerably, depending on what is to be sampled (see Chapter 5).

Intraspecific genetic diversity is the most basic measure of biodiversity. Monitoring of genetic variation within species, through assessment of genomic markers (e.g. microsatellites) or through direct genome sequencing, is required to assess population connectivity or changes in heterozygosity (e.g. levels of inbreeding) resulting from ecosystem impacts. eDNA or metagenomic approaches enable the assessment or monitoring of species presence / absence. Such approaches can be quantitative or semiquantitative and are subject to specific biases (as are all forms of biodiversity survey). These approaches can be used in the detection of pathogens, harmful algal blooms (HABs) and invasive species.

Animal tagging and telemetry is used to analyse patterns of behaviour and migration (e.g. to understand connectivity, foraging and breeding grounds, migration corridors). Tags are increasing in sophistication (i.e. in what they can measure) and reducing in size. They can also enable the use of animals to undertake oceanographic measurements in areas which are difficult to access using conventional infrastructures. Active and passive acoustics can also be used to understand patterns of behaviour (e.g. diurnal vertical migration), biomass (e.g. biological acoustic measurements of pelagic fish biomass), species presence / absence (e.g. cetaceans) and ecosystem health.

Measuring the Environment

Physical and biogeochemical drivers determine the spatial and temporal distribution of populations, species and communities, including seasonal changes, natural decadal-scale variation and extremes of these parameters. As with almost all the other Grand Challenges, there is a cross-cutting requirement to ensure that Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs) Frameworks are developed (Muller-Karger et al., 2018). Physical variables include measurement of temperature, salinity, currents, and other physical parameters that influence marine biodiversity. Biogeochemical parameters include concentrations of macro- and micro-nutrients, pollutants, and other chemical substances in the water. It is important that such measurements can be carried out concurrently with biodiversity or monitoring although global datasets, such as sea surface temperatures obtained by satellite remote sensing, can be used to understand the drivers of species distribution.

Ecosystem Function and Dynamics

The relationship between biodiversity and ecosystem function is fundamental to understanding the impacts of biodiversity loss as well as how biodiversity underpins ecosystem services. There is therefore a need to develop approaches to estimate ecosystem function at the level of communities, functional groups and even individual species (Ruhl et al., 2021). Such measurements are important in ecological and biogeochemical model development and validation. Ecosystem function can be related to estimates of ecosystem service provision and in turn ecosystem valuation.

A cross-cutting requirement in improved understanding of biodiversity and links to biogeochemistry and climate, is the measurement of rates of primary and secondary production. These measurements can be achieved through measurements of rates of photosynthesis and biomass production in marine ecosystems and the way they vary spatially and temporally. Export of production from the epipelagic zone into the deep sea is an important term in the ocean carbon pump and can occur through the gravitational sinking of phytodetritus and other biological material (marine snow) or through mechanisms of active biological repackaging or transport (e.g. through diurnal vertical migration). Monitoring the flow and recycling of other nutrients within marine ecosystems, such as in the nitrogen, and phosphorus cycles, is also a significant requirement for understanding ecosystem function and dynamics. Such measurements are currently undertaken through combinations of satellite remote sensing, near shore and offshore ship-based measurements and experimentation, and increasingly through the use of autonomous platforms equipped with sensors for measuring the physicochemical parameters influencing the carbon pump and nutrient cycles, as well as to measure the diversity and abundance of the biological communities which drive these processes.

As well as understanding primary and secondary production, it is important to understand species interactions and trophic dynamics, including predator-prey relationships and energy transfer through food webs. This often requires *in-situ* sampling and experimental approaches carried out at sea with laboratory analyses including isotopic approaches, biomarkers and diet analysis (sometimes using genetic approaches such as barcoding). The use of tags equipped with cameras is now providing the ability to record live feeding events in large marine predators such as sharks and cetaceans. Understanding metabolic rates also requires experimental approaches to measuring aspects of physiology such as respiration. In shallow waters, it can be possible to capture organisms and measure such parameters through laboratory incubations or adopt whole community approaches through *in-situ* methods. Obtaining such data from the deep sea is particularly challenging, requiring the deployment of landers with oxygen sensors.

Assessment of Human Impacts

Assessing the impact of human activities, such as extraction of living (e.g. fishing) and non-living (e.g. marine mining, aggregate extraction) resources, pollution, and coastal development on marine biodiversity, is a significant requirement of biodiversity science. Such assessment is fundamental to sustainable management of human activities in the ocean (see blue economy below). In addition, there is a need to evaluate and monitor the effectiveness of spatial and other conservation measures in protecting biodiversity. Such assessment is typically undertaken using Before-After / Control-Impact approaches which typically involve surveys of *in-situ* biological communities. Inshore, these can comprise destructive and non-destructive intertidal or shallow subtidal surveys using SCUBA divers whilst offshore, ship-based surveys using ROVs, submersibles, towed cameras and over-the-side sampling such as trawls or corers can be used. For intertidal to shallow-subtidal communities in clear water satellite remote sensing or remote sensing using aircraft or aerial drones can also be used for community assessment. Increasingly, autonomous technologies are being used for survey of subtidal to deep-sea ecosystems. Laboratory studies of taxonomy of samples are often required for species identification with eDNA / molecular barcoding approaches increasingly adopted for monitoring of biological communities. Acoustic approaches, deployed from ships, AUVs, ASVs or static hydrophones are also important for habitat mapping (e.g. through analysis of backscatter), assessment of population size (e.g. fisheries acoustics) or the presence / absence of threatened species (e.g. cetacean monitoring with hydrophones). Assessment of pollution impacts may require *in-situ* or laboratory studies of exposure / mortality risk in marine species (see Pollution). Assessing the health and condition of habitats can also be undertaken through indicators like water quality, substratum type, the occurrence of disease, and presence of key species.

Data Integration

Biological data of the type needed to study biodiversity can be very complex, for example comprising image data, species identification information, DNA sequence information and data on the physical and biogeochemical environment. Some of these data types require significant data storage capacity likely undertaken through cloud-based solutions. It is important to integrate data from various sources and platforms to create comprehensive and accessible (FAIR) datasets for use by ecologists, modellers and ocean managers so metadata standards are likely to be crucial along with adoption of common standardised vocabularies for biodiversity and other types of data (e.g. Darwin Core). Adoption of AI / machine learning approaches are already advancing swiftly, particularly in the use of computer vision for image annotation and extraction of data from video surveys.

A UK marine biodiversity hub was identified to provide a centre of excellence for measurement and forecasting (modelling) of marine life. A hub and spoke arrangement was suggested for this with external organisations including, for example, the Wellcome – Sanger Institute, the National Centre for Coastal Autonomy and the Turing Institute, as well as national museums and other taxonomic collection centres and universities with significant programmes in biodiversity research. The hub would also link to international institutions and databases such as the Ocean Biodiversity Information System (OBIS).

10.2.3. Marine Pollution

The wide range of pollutants, their speciation, distribution and transport in the environment, as well as biological effects when multiple chemicals are present, along with cumulative, synergistic or antagonistic effects of other stressors arising from global climate change and direct human impacts such as overfishing, present a complex set of requirements for future science in this area. Measurements of pollutants from discrete water or sediment samples, as well as *in-situ* incubations of sediment including for sediment-water interactions, are often required. Measurements in air may be important for chemical pollutants with a high volatility, or which may be dispersed as aerosols or particulates.

More rapid and accurate measurement of radioactivity and radioactive materials in the environment are also needed including, for example, better measurements of tritium in the environment as well as long-lived elements in nuclear waste and naturally occurring radioactive materials (NORMs) which may result from e.g. oil and gas extraction.

Satellite remote sensing for oil spills requires improvement through the development of image databases for algorithm improvement by comparing real oil spills with lookalikes. New 'multi or hyper' band radar sensors may lead to improved detection through elimination of detection errors.

High sensitivity measurements of pollutants from water, sediment and tissue samples are required. It is important that standardised, reproducible, accurate and precise measurements can be performed across different laboratories following best practice (e.g. through the Ocean Best Practice System). Adoption of Certified Reference Materials (CRMs) to ensure that laboratories are measuring consistently with their equipment is often a core component in quality assurance.

Controlled exposure experiments to better understand the impacts of pollutants on organism physiology (e.g. impacts on the immune, nervous and reproductive systems), the overall toxicity of pollutants and the combined impacts of multiple pollutants on species and communities under different conditions are needed. Such experiments should not only target adult organisms but also different life-history stages of species.

Understanding changes in pollutants over time, as well as being able to assess past samples with new technologies, will need archiving and preservation of samples. In addition, centralised data repositories alongside the computational infrastructure to support processing of large datasets are also viewed as important to advance this area of science. This will also include the need to increase model and statistical capabilities. These capabilities can be leveraged using big data analytics including integrated, diverse data sources; predictive models, including hydrodynamic modelling, such as pollution dispersion and ecosystem impact models; and statistical risk models and/or Probabilistic Risk Assessment (PRA) to assess the probability and potential impact of pollution events.

Development of AI to improve interpretation of remote sensing data from space for rapid/large area surveys is another requirement for specific areas of marine pollution research. Machine learning algorithms, particularly Convolutional Neural Networks (CNNs), can analyse images from satellites (and drones equipped with a high-resolution camera) to detect oil spills, plastic waste, and other pollutants in the ocean. AI-powered geospatial analysis tools can create maps of pollution distribution, helping to identify pollution sources.

Collaborations and knowledge sharing between facilities and disciplines are viewed as critical to meeting the requirements of pollution science in maximising the science impact for research investment in this area. Interdisciplinary scientific field studies and collaborations are seen as an important element of greater cooperation.

To tackle the issue of pollution, Chapter 6 also emphasised the needs for education and raising awareness, and for better engagement with industry and other stakeholders on research. Increasing dialogue around management strategy to prevent, mitigate, reduce, and regulate pollution. This will require an integrated approach that combines regulatory frameworks, technological advancements, industry best practices, and community engagement. Whilst Chapter 6 also identified the creation and evaluation of advanced waste treatments to mitigate pollution risks, it also identified the importance of development of new technologies and methods for sustainable production processes. Access to industry data is also important to understand pollutant chemistry, methods of production and to quantify how much pollutants are being generated.

10.2.4. Hazards and Extreme Events

Hazards and extreme events occur both nearshore, in coastal environments, as well as offshore, and vary in terms of frequency, magnitude of impacts and rates of change. The globalisation of the world economy means that even distant events, elsewhere in the globe, can impact on supply chains, the economy and society of the UK and other countries. Therefore, there is a need to both understand the risks posed by low-frequency but high-impact natural events and high-frequency, lower magnitude events, which cumulatively may have large impacts. Both geological and meteorological risks must be assessed using a multi-hazard and impact-based approach (Chapter 7). This means that marine hazard research must be cross disciplinary, spanning oceanography, geology, geophysics, meteorology, biology, engineering, spatial planning, policy, economics and the social sciences.

Given the cross-disciplinarity of hazards and extreme events research, there is unsurprisingly considerable overlap in science requirements with the other Grand Challenge chapters. For example, the need for baselines, including for climatic measurements, seafloor and sub-seafloor geology and for marine ecosystems, including biodiversity are shared with the requirements for climate, biodiversity and blue economy science. High resolution observational and sampling datasets for climate and meteorology, particularly in coastal and nearshore environments, are required to inform spatial planning and marine engineering, climate modelling and forecasting, a shared requirement with the Climate Grand Challenge and important input into understanding changes in biodiversity. High-resolution marine geology datasets are also needed in the coastal zone, including monitoring temporal seabed evolution, including pre- and post- event data and seabed morphodynamics, to advance hazard management strategies. Such high-resolution datasets form important inputs into modelling, informing the UK's National Risk Register including the Regional Environmental Prediction (REP) modelling approach adopted by the Met Office.

In addition to coastal-zone observations, there is a need for geological and geophysical surveying and sampling at and beneath the ocean floor. This includes active and passive seismic surveying, controlled source electromagnetic characterisation, magnetic and gravity surveys, and geological sampling (e.g. coring). Such measurements are fundamental to improving our knowledge and understanding of the planetary processes that govern natural hazards, and in understanding the frequency, magnitude and impacts of past events. Globally, subduction zones and volcanic arcs of the western Pacific and Indian oceans are a particular gap in our knowledge of past events and sub-surface structure and processes. Generally, there is a need for high-resolution sub-seafloor datasets, with more comprehensive spatial coverage to advance understanding of processes and mechanisms driving geological hazards, and in improving records of past extreme events and their consequences.

There is also a requirement for generation of real-time geophysical data, for example, on ocean currents, seismicity and volcanic activity. Such monitoring can be enabled through the use of ocean observatories (fixed installations of instrumentation or sensors and/or repeat sampling stations) or new technologies such as cable sensing. These can significantly enhance existing long-term monitoring programmes on meteorological or geological hazards by adding new data or new datasets. It will also be necessary to adopt new technologies in transmission of such data in real time to land and specifically to agencies involved in hazard prediction, mitigation and response.

In keeping with the other Grand Challenges, the Hazards and Extreme Events chapter also identified the need for increased data storage and accessibility including for new and diverse high-resolution datasets. New high-resolution model development was also identified as a requirement to improve hazard and extreme event prediction, likely including machine learning / artificial intelligence approaches. The development of Digital Twins, such as the Destination Earth (DestinE) project, for prediction of hazards and for the development of adaptation and mitigation strategies, will likely be part of this. Better models will require higher spatial and temporal resolution measurements of deep ocean and coastal processes and increased global sensor coverage, particularly in sensitive areas, including satellite remote sensing, for oceanographic and geological hazard modelling and prediction.

10.2.5. The Blue Economy

In Chapter 8, two types of knowledge were identified as of high importance in the development of sustainable commercial activities. The first is monitoring of the impacts of industries at sufficient spatial and temporal resolutions to avoid significant harm to the environment. The second is the knowledge required by blue economy participants to ensure that their activities are sustainable socially, economically and environmentally. Both of these requirements crossover strongly with other Grand Challenges. For example, for many blue economy sectors active in the coastal zone, such as fisheries, aquaculture and renewable energy, high resolution monitoring and forecasting using remote sensing and *in-situ* measurements, including EOVs, are key to short-term operational needs and longer-term industry planning (e.g. how changing climatic conditions will affect the viability of fish stocks or aquaculture species; optimal spatial placement of wind turbines etc.). As with the Grand Challenges on Pollution and Hazards, there is a need in supporting the sustainable blue economy to develop methods to assess the cumulative impacts of multiple activities. As described in the Grand Challenges for Climate, Biodiversity and Hazards there are needs to establish baselines in a range of oceanographic, biodiversity and geological parameters.

With the blue economy, as with almost all the other Challenges, there will be demand for the real-time acquisition of data from a range of observational platforms, as well as its storage and integration, so that it is accessible and actionable on relevant timescales for decision making by industry, governments and civil society. More advanced modelling will be required for the rapid analyses of such data, including the use of AI and Digital twins important for the prediction of ocean state and the impacts of human activities.

As with Chapter 6 on Pollution, the sharing of industry data for science purposes is seen as important for advancing support for the blue economy. However, it is taken further here as industry (and civil society) has enormous potential to increase the spatial and temporal resolution of data collection through the use of their platforms/infrastructure. Industry also has significant data holdings and bringing this together with research data, and legacy data into unified repositories to enhance accessibility, integration, and use in supporting the sustainable blue economy would be helpful. These will require the establishment of collaborative frameworks that will help promote integrated approaches to marine research and management through sharing observations, knowledge, data, resources, and best practices across sectors. As with the other Grand Challenges, there is also the need to develop more engagement and education programs that translate scientific data and research findings into accessible information for policymakers, industry and the public.

As well as these broad requirements of science supporting the blue economy, more specific science requirements were also identified. These include:

- Research into dynamic marine spatial planning that incorporates environmental changes and sectoral impacts.
- There is a gap in research underpinning private sector investment in offshore carbon sequestration and storage. More scientific research is needed to assess the environmental, climate and economic viability of marine carbon dioxide removal and CO_2 storage.
- Research is needed to understand the ecosystem level trade-offs between different food production systems and ecosystem services.
- Research to develop more sustainable fishing practices are required.
- Understanding the impacts of environmental changes on species growth, disease, and ecosystem interactions within aquaculture is needed.
- There is still a gap in knowledge in models for fisheries is recruitment, and its drivers, especially under the effects of climate change.
- Research is required on the potential impacts of climate change on shipping patterns.
- Operation of autonomous ships will require improved metocean data as well as for the instrumentation of such vessels and their operation through the use of digital twins.

10.3. Global Developments and International Best Practice.

The ocean is a complex and highly connected component of a broader global planetary system where physics, chemistry, geology and biology intersect at all spatial and temporal scales. While the UK is already a global leader in many of the marine science areas described above and has both the capability and capacity to undertake large scale research and observational programmes, because of the scale of the system, no single nation can measure all aspects of the marine environment to manage their interests; collaboration with international partners is essential. Global programmes and frameworks enable nations to collaborate towards these common goals, ensuring contributions come together in a way that is greater than the sum of its parts. Indeed, marine science has a long-established history of international partnerships and collaboration, with the key role the UK exercises in this field, as underpinned by a world class research infrastructure, representing global leadership.

10.4. The Global Ocean Observing System (GOOS)

The UN's GOOS is sponsored by the World Meteorological Organisation, Intergovernmental Oceanographic Commission, UN Environment Programme and the International Science Council. GOOS focuses on enabling large scale sustained ocean observations (Figure 10.1) and communicates the case and requirements for such observations through the UN system to member states, evaluates requirements for sustained ocean observations through internationally agreed Essential Ocean Variables (EOVs; Miloslavich et al., 2018; Figure 10.7) and reviews implementation through globally coordinated networks.

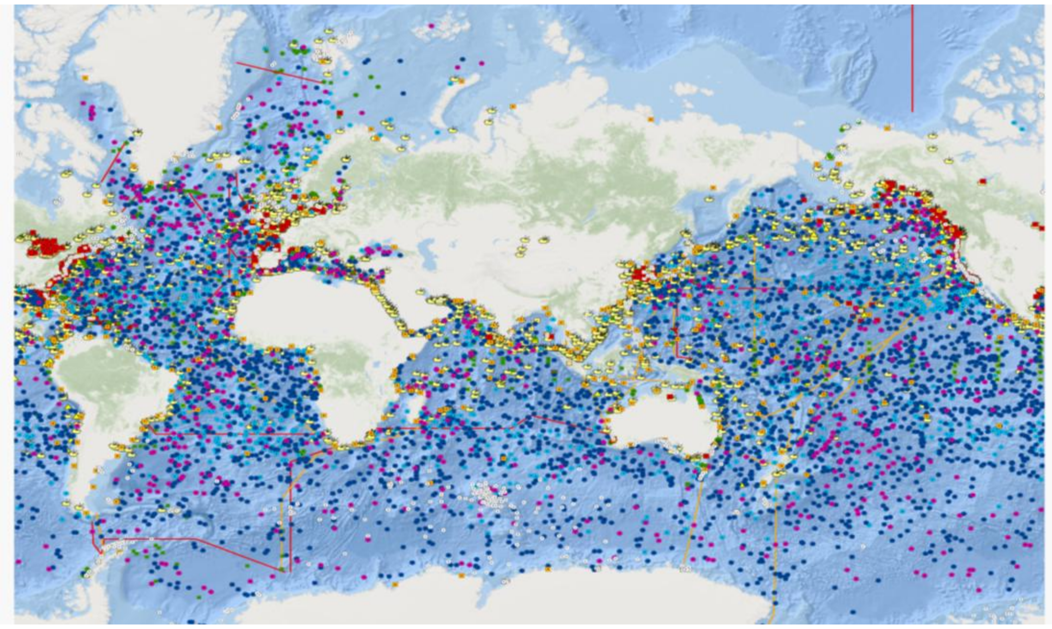

Figure 10.1: Schematic of the Global Ocean Observing System (Source: *www.ocean-ops.org*)

The original GOOS design was motivated largely by the need to deliver climate relevant observations and was developed in collaboration with the UN Global Climate Observing System (GCOS)[13], which then agreed Essential Climate Variables (ECVs; Bojinski et al., 2014). GCOS

[13] WMO-IOC-UNEP-ISC Global Climate Observing System (GCOS)

submits Implementation Plans[14] to the UN Framework Convention on Climate Change which provides a legal framework to request member states to measure ECVs[15]. The GCOS monitoring principles[16] provide a framework of best practice for climate observations to ensure trust in the climate record, including managing changes in observation technologies.

In 2012, the 'Framework for Ocean Observing' was developed to provide a framework to guide the development and evolution of the GOOS to meet an expanded range of uses and users, beyond climate (Figure 10.2). The framework identified the need to articulate requirements for the observing system using Essential Ocean Variables (EOVs) in order to determine observing system design and implementation through observing networks, which then deliver data to support a range of applications and feed back into evolving the requirements.

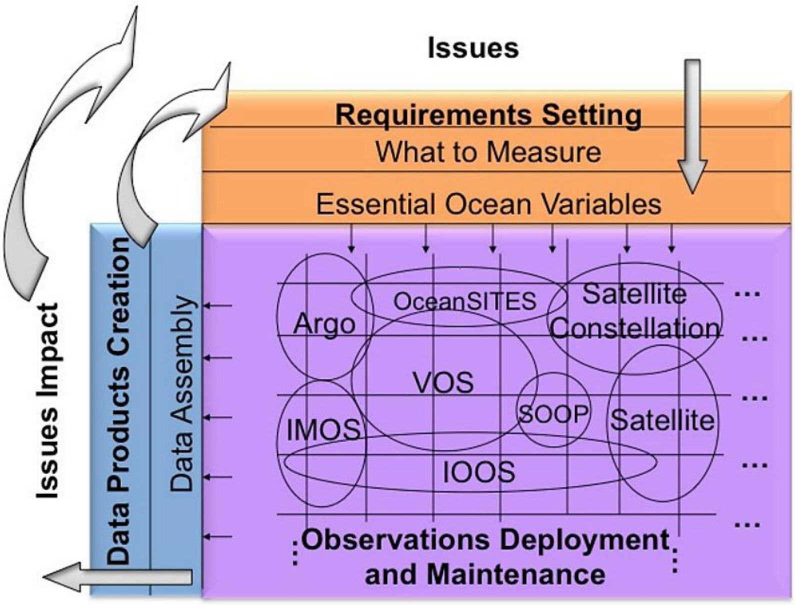

Figure 10.2: Introducing a Framework for Ocean Observing, shaped by requirements. **"Structure of the Framework for Ocean Observing.** How ocean observing activities fit into the systems model of the Framework. The critical feedback loop between observing system outputs and science-driven requirements is shown. (Observation system examples are illustrative only, not comprehensive)." Source: A Framework for Ocean Observing, by the Task Team for an Integrated Framework for Sustained Ocean Observing (IFSOO).

Building on the concept of ECVs and aligned with Essential Variables (EVs) for weather and the emerging Essential Biodiversity Variables (EBVs; Pereira et al., 2013), GOOS agreed a set of EOVs which should be observed globally, with requirements specified (Figure 10.3). These are driven by requirements, negotiated with feasibility – recognising we cannot measure everything measurable at scale, but rather focusing on the key observables required for large-scale long-term monitoring. EOVs provide the basis for including new elements of the system, for expressing requirements at a high level, allowing for innovation in the observing system over time. The EOVs will be discussed further in chapter 11, the synthesis of requirements.

[14] GCOS Implementation Plan 2022
[15] UNFCCC - Research and Systematic Observations
[16] GCOS Monitoring Principles https://gcos.wmo.int/en/essential-climate-variables/about/gcos-monitoring-principles

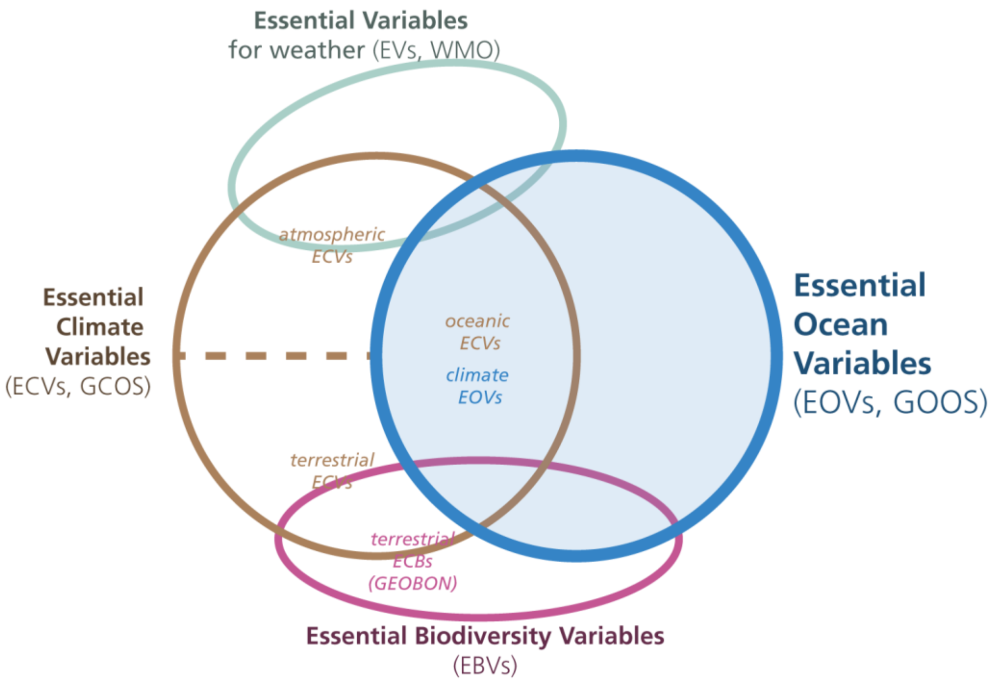

Figure 10.3: Essential Ocean Variables and relationship with other variable requirements. Note: Terrestrial ECBs should read terrestrial EBVs.

The Framework for Ocean Observing has been exercised by a number of programmes to advance their evolution – including development of observing networks, design, development and review of regional observing systems, and development of national systems. The Framework for Ocean Observing is focused on the development of the sustained observing system, so it is important to consider how we develop and target both sustained and experimental observations and the interplay between the two.

10.5. Beyond Implementing Observations to Deliver Information to Society

While ensuring an observing system is implemented is important, it is also recognised this is not sufficient. Greater effort is needed on extracting value from the observations collected. The GOOS 2030 Strategy[17] envisions '*a global ocean observing system in 2030 that is responsive to the needs of end users. Information relevant to climate, operational needs, marine ecosystem health and human impacts will flow from locally and remotely sourced ocean observations'* (Figure 10.4). The Strategy recognises that, beyond ensuring that observing equipment is deployed to collect measurements, further effort is needed once the data comes off the observing platforms to ensure that data is findable, usable and delivering fit for purpose products and information to society at timescales appropriate to societal needs. This will require strengthened partnerships at national and international levels.

[17] Global Ocean Observing System (GOOS) 2030 Strategy

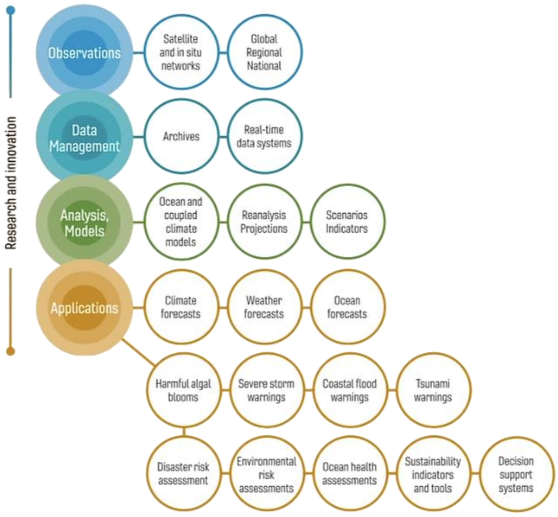

Figure 10.4: The complex chain of actions and actors to move global ocean observing beyond the scientific realms to deliver fit for purpose observations and information to society (GOOS 2030 Strategy).

The agreement of the UN Sustainable Development Goals in 2021 marked the start of the UN Decade of Ocean Science for Sustainable Development (2021-2030). The UN Ocean Decade identified 10 Decade Challenges[18] - three of which are explicitly infrastructure challenges (in bold), focused on strengthening observational, digital and human capabilities, while the other Challenges are all underpinned in multiple ways by observing and experimental infrastructure.

1. Understand and beat marine pollution.
2. Protect and restore ecosystems and biodiversity.
3. Sustainably nourish the global population.
4. Develop a sustainable, resilient and equitable ocean economy.
5. Unlock ocean-based solutions to climate change.
6. Increase community resilience to ocean and coastal risks.
7. **Sustainably expand the GOOS.**
8. **Create a digital representation of the ocean.**
9. **Skills, knowledge and technology for all.**
10. Restore society's relationship with the ocean.

While hundreds of individual actions have been spun up through the Decade, Decade Collaborative Centres (and Coordination Offices) aim to coordinate across relevant projects to deliver a legacy of boosted coordination beyond the Decade (Figure 10.5). Of particular note are the Decade Coordination office for Ocean Observing, the Coordination office for Data Sharing and the Collaborative Centre for Ocean Prediction as three core hubs of coordination underpinning decade action – this reinforces an international drive towards bringing our

[18] UN Decade of Ocean Science for Sustainable Development – 10 Decade Challenges

observational and digital infrastructure together. ‘Vision 2030’ community Whitepapers were developed for each of the Challenges, and the recommendations synthesised in a ‘Pathway to 2030’ document (UNESCO-IOC, 2024).

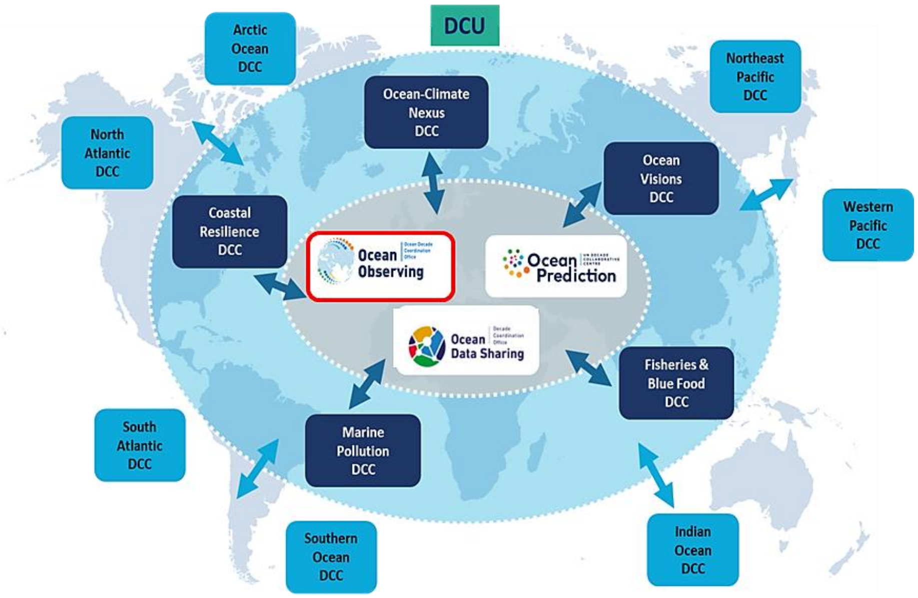

Figure 10.5: Coordination of the UN Ocean Decade: Comprising the Decade Coordination Unit (DCU), Coordination Offices (DCOs) and Collaborative Centres (DCC), with coordination of Ocean Observations, Data and Prediction at its core.

Building on the UN Ocean Decade and the broader UN Agenda 2030 (Sustainable development goals), the recent EMB ‘Navigating the Future’ policy brief (European Marine Board, 2024) positions ocean science at the centre of the wider earth system and highlights the crucial role the ocean plays in Earth’s interconnected systems and outlines a vision for future marine research and policy. Organised around four key themes – People, Climate, Freshwater and Biodiversity – the paper called for more funding for integrated, transdisciplinary research and governance approaches to safeguard the ocean and its essential role in Earth’s systems. Key cross cutting requirements were identified including key requirements of relevance to FMRI; needs for sustained long term research funding, sustained ocean observations, accessible data, people trained to collaborate (see Figure 10.6).

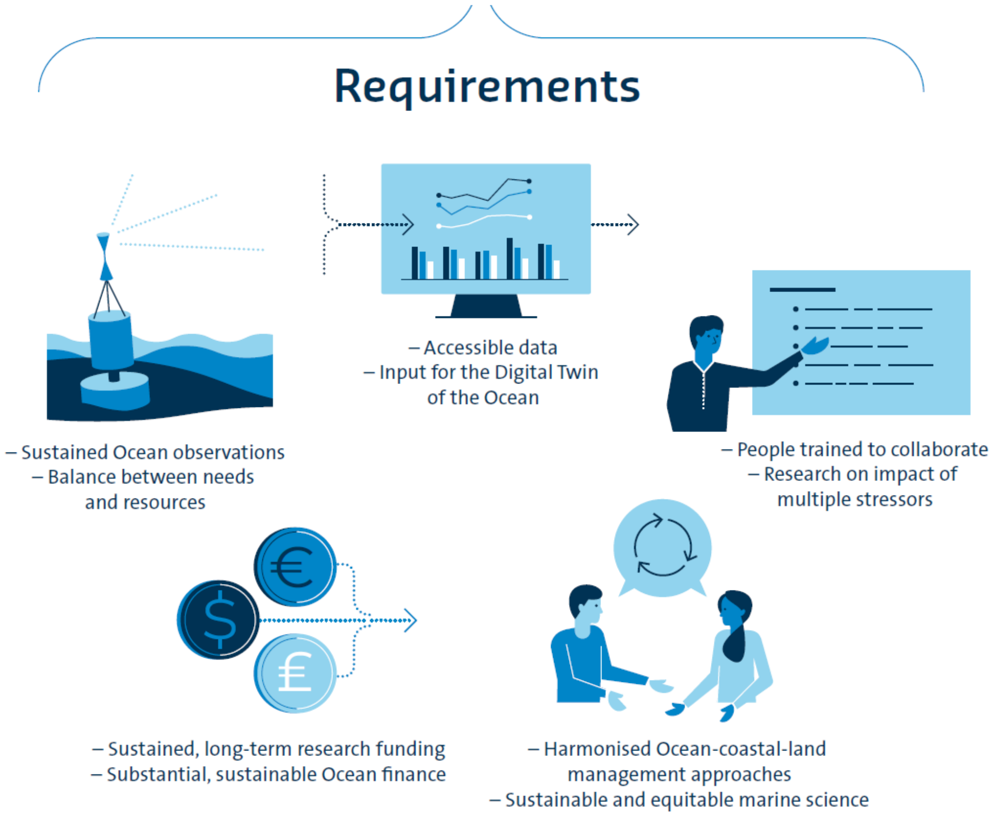

Figure 10.6: Cross cutting requirements for future marine research identified in the European Marine Board 'Navigating the Future IV' Policy Brief.

Marine research infrastructure is critical for research into the broader earth system within the marine domain, including the atmosphere, the water column, the seafloor and earth's crust.

The International Ocean Drilling Programme (IODP), responsible for leading scientific ocean drilling worldwide, developed a new Science Framework for 2050 (Koppers and Coggon, 2020) with a focus on 7 Strategic Objectives that are similar in nature to the 10 Decade Challenges:

1. Habitability and Life on Earth
2. Ocean Life Cycle of Tectonic Plates
3. Earth's Climate System
4. Feedback loops in the Earth System
5. Tipping Points in Earth's History
6. Global Cycles of Energy and Matter
7. Natural Hazards Impacting Society

The recent change in drilling ship capability globally has impacted IODP, following the retirement of the US-operated *JOIDES Resolution*. Launched in January 2025, IODP[3] continues to make use of Mission Specific Platforms operated by the European Consortium for Ocean Research Drilling (ECORD), and the riser drill ship *Chikyu*, operated by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). The community is also exploring how to make use of archive cores and data, e.g. through new analytical approaches and Artificial Intelligence (AI)/Machine Learning (ML) techniques, while enhancing the international partnerships and continuing to push for new state-of-the-art drilling platforms for the scientific community. The UK's membership of IODP[3] is made possible via a NERC subscription to ECORD, who are a core member of IODP[3] alongside JAMSTEC.

There is a plethora of ongoing international collaborative programmes, such as *inter alia* the World Climate Research Programme (WCRP) (discussed in the Climate Grand Challenge), Future Earth, Past Global Changes (PAGES), in addition to a range of important programmes developed through the UN ocean Decade.

10.6. Net Zero Oceanographic Capability – Future Science Needs

The UK's Net Zero Oceanographic Capability (NZOC) Report was developed to investigate how de-carbonisation of the marine observing infrastructure can contribute towards UKRI's objective to be net zero by 2040, itself a reflection of the UK Government's lead on climate action (National Oceanography Centre, 2021). This net zero requirement presents a challenge to the marine science community as to how to maintain and advance marine science whilst reducing its carbon footprint (National Oceanography Centre, 2021). Solutions investigated in the NZOC report included a major shift in the development of marine infrastructure with an expansion of autonomous platforms and sensors to undertake more science observations than carried out at present on existing autonomous platforms and vessels, whilst shipboard science would be undertaken by new research vessels, fuelled by low-emission energy sources such as ammonia or hydrogen (National Oceanography Centre, 2021). Alongside this 're-envisaging' of UK marine infrastructure, further needs were identified in improved end-to-end data management and flows to enable more complete and FAIR access to data, as well as better connectivity to enable improved modelling capability, such as through Digital Twins, as well as application of technologies such as AI and machine learning (National Oceanography Centre, 2021).

The NZOC report analysed many of the requirements identified as needed by the Grand Challenge and other chapters in the SRF. Here we summarise some of the main findings relevant to the SRF, to provide some contextual link between this and the NZOC report. For future science requirements the NZOC report concluded:

- Scientists are increasingly using marine autonomous systems to collect data.
- Marine science is increasingly multidisciplinary and the global marine science questions, drivers and applications demand multidisciplinary approaches.
- Multidisciplinary marine science will require coordinated data collection.
- International collaboration is increasing and may allow for the efficient use of research vessels, ship-deployed equipment and autonomous platforms (e.g. through barter systems or coordinated investment in infrastructure).
- Investment in both technical development and ongoing operation of cutting-edge infrastructure remains necessary for UK marine research to retain its international world leading position.
- Available bandwidth on research vessels should be significantly increased to support remote participation (e.g. telepresence) and outreach activities wherever possible.

- It is necessary to consider how to train scientists to access new technologies developed through an NZOC programme (e.g. autonomous platforms, new sensors).
- There should be a deliberate investment in an equitable, diverse and inclusive marine science community able to take advantage of how new technology can remove barriers.
- Improved links to industry are needed to adopt useful technologies early.
- The use of international programmes to expand UK ocean observing capabilities will continue.

The NZOC report also detailed ways in which marine science is increasingly aimed at benefiting society. Specific recommendations included a public-facing knowledge platform on ocean health to support public engagement, with critical ocean issues and closer working relationships between UK marine scientists, government and government departments and agencies.

Adoption of carbon emission reducing fuels for the research vessel fleet are likely to focus on lower energy density fuels such as ammonia or hydrogen. The use of such fuels will likely change the design of research vessels to maintain operational capabilities and endurance as well as the number of crew and scientist berths. Such designs may involve trade-offs in various specifications and hence capabilities and/or capacities. Furthermore, at present the global shipping industry has not settled on the optimal low emission fuel(s), a necessary precursor to the development of port infrastructure for bunkering such vessels globally (McKinlay et al., 2021). For example, whilst ammonia has a high energy density, it is also toxic and highly corrosive, whilst the supply of methanol is difficult to decarbonise (McKinlay et al., 2021). Hydrogen has a low energy density but is easier to decarbonise its supply and cryogenic storage can reduce storage issues (McKinlay et al., 2021). Until industry demonstrates a clear path ahead, investment in any particular fuel technology is a risk although there has been a trend towards hydrogen propulsion in studies of future zero emission research vessels (e.g. Madsen et al., 2020). In the interim, the NZOC report outlined the potential to reduce the emissions of the current research vessels through:

- Route optimisation
- Hull form optimisation
- Wind assistance technologies
- Advanced hull coatings
- Speed reduction
- Main engine improvements
- Auxiliary systems improvements
- Modification to allow ships to ‘plug in’ to green shore electrical supplies
- Sustainable food policies
- Use of low carbon ICE fuels such as biodiesel

Autonomous platforms have advanced considerably over recent years for applications in the offshore energy sector, ocean science and defence (National Oceanography Centre, 2021). The growth in use of such platforms is expected to increase in the future, with increasing opportunities for UK ocean science institutions for commercialisation of technology innovation in autonomous platforms. The NZOC report identified that science requirements were driving the need for further advances in autonomy including:

- Extension of the endurance of autonomous platforms.
- The development of coordination of multiple platforms to work together (drone swarms).
- Improved operational control and management to avoid collisions especially in the coastal zone.
- Advancement of Onboard-Control-System (OCS) and shore side Command and Control of autonomous platforms including to improve under ice operations.
- Improved abilities to operate near or on the seafloor (e.g. hovering AUVs).
- Improvements in launch and recovery systems to allow greater flexibility of use.
- Improved battery / fuel cell technology.
- Improved biofouling solutions.
- Development of fleet planning tools and improved data flows.

Taking full advantage of improved autonomy will also require the development of sensors, including systems to measure the physical and biogeochemical parameters of marine ecosystems, and to quantify and identify marine life (National Oceanography Centre, 2021). Examples of where sensor development is already underway is the use of AI for the classification / annotation of marine organisms from image data and the use of genomic technologies for monitoring of species from environmental DNA samples (eDNA; National Oceanography Centre, 2021). As with the Grand Challenge in Biodiversity, the development of an expert hub in sensor development was considered to be an effective way forward providing a centre of excellence in measurement systems (National Oceanography Centre, 2021). This hub could include spokes supporting external organisations with special expertise in particular sensor technologies, for example, satellite remote sensing or animal tagging. Standardisation of design parameters, modules, and interfaces would be required to guide sensor developers in the hubs and spokes, enable efficiency and as far as possible a 'plug and play' approach to platform integration (National Oceanography Centre, 2021).

As with all the Grand Challenge chapters, there was a recognition within the NZOC report that current processes for handling of data from the point of generation on platforms to ingestion by databases were still slow and time-consuming. Expansion of the ability to generate data means that it is essential to automate data processing from the point of production to access by end users (National Oceanography Centre, 2021). Data management processes will be required that incorporate quality and metadata controls and enable the transfer of data-to-data portals that allow access across a broad community of users (i.e. FAIR access; National Oceanography Centre, 2021). The integration of data collection, modelling, data sciences and informatics could enable 'digital twins' of the ocean which could receive inputs of data in real or near-real time for more accurate forecasting at regional to local scales, as well as longer range environmental change prediction (National Oceanography Centre, 2021). Standardisation of data protocols across platforms and across the global research community are important elements of expanding ocean observation, data accessibility and communication. Data security (cybersecurity) was also identified as an important issue to consider, and this has only become more apparent over time. Plans for training the future generation of scientists and engineers/operators capable of developing, operating and using a digitally enabled, ocean observation system is also essential.

It is important to recognise the challenges that were identified in the NZOC programme. These included:

- The costs of transition to a new configuration of marine infrastructure whilst maintaining legacy infrastructure. This included transitional changes in ships to reduce the CO_2 footprint prior to availability of new widely adopted propulsion technologies.
- Access to skilled human capacity in a market where there is a lot of competition for staff with similar skills.
- The need for behavioural shifts, aimed at reducing carbon footprints across many aspects of doing ocean science (e.g. sharing of data; use of telepresence).
- Issues around regulation, for example, around the use of autonomous platforms in inshore waters.
- Cybersecurity and other security concerns.
- Biofouling of sensors and platforms that stay in water for extended periods of time, impairing their operation.
- Technological and methodological lock-ins that prove to reduce scope for future implementation and development of sustainable ocean science.
- There remain areas of science identified through the Grand Challenges that are currently only possible to progress using research vessels.
- Changes in technology will disrupt some long-term datasets.

Given these barriers to development of future marine infrastructure, as well as funding constraints, ensuring that science requirements are met may require investments over an extended period of time.

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10.8. Annex

Most of the EOVs (in orange) have community developed specification sheets which outline the phenomena to capture, scales, and accuracies required as well as current observational components that contribute to meeting those requirements.

Physics	**Biochemistry**	**Biology and Ecosystems**
Sea state Ocean surface stress Sea ice Sea surface height Sea surface temperature Subsurface temperature Surface currents Subsurface currents Sea surface salinity Subsurface salinity Ocean surface heat flux Ocean bottom pressure Turbulent diapycnal fluxes (*pilot)	Oxygen Nutrients Inorganic carbon Transient tracers Particulate matter Nitrous oxide Stable carbon isotopes Dissolved organic carbon	Phytoplankton biomass and diversity Zooplankton biomass and diversity Fish abundance and distribution Marine turtles, birds, mammals abundance and distribution Hard coral cover and composition Seagrass cover and composition Macroalgal canopy cover and composition Mangrove cover and composition Microbe biomass and diversity (*pilot) Invertebrate abundance and distribution (*pilot)
Cross-disciplinary (including human impact)		
	Ocean colour Marine debris (*pilot)	Ocean sound

Figure 10.7: GOOS Essential Ocean Variables (Global Ocean Observing System; *www.goosocean.org*).

Chapter 11: Recommendations and Priorities

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The UK remains an international leader in marine science, as evidenced through the citation impact of UK publications in this field being amongst the highest globally, (Department for Science, Innovation & Technology, 2025) and a strong track record in collaborative science (Mitchell *et al.*, 2020). Through active involvement in international programmes, such as the Intergovernmental Oceanographic Commission (IOC), the Global Ocean Observing System (GOOS), World Climate Research Programme (WCRP) and the UN Decade of Ocean Science, the UK contributes significantly to global understanding of marine science and advances evidence-based ocean stewardship in the face of a triple planetary crisis. This places the UK in a unique position to influence ocean governance for the benefit and security of the economy and wider society, and to exert a positive influence internationally through treaties, agreements and capacity development activities with low- and middle-income countries. Maintaining leadership in marine science internationally means continued investment in marine infrastructure including ships, autonomy and sensors, as well as rapidly adopting the technologies of the digital transformation to ensure flows of data to stakeholders at relevant timescales, to facilitate efficient, effective, decision making. Investment in UK marine research infrastructure thus provides the scientific capabilities and capacities to support and strengthen its leadership position through enabling critical underpinning knowledge and innovation in many aspects of marine science. This includes the development of a sustainable blue economy, for operational weather forecasting and protection of coastal communities from marine hazards at short to long timescales, for predicting, mitigating and adapting to the effects of climate change, for the restoration and conservation of marine biodiversity and ocean health and for enhanced underpinning knowledge and understanding of the broader Earth system.

The Science Requirements Framework has synthesised the UK's marine science needs. These range from the strategic importance of knowledge to drive a thriving blue economy and to provide security for society from environmental change, to meeting commitments on international treaties and agreements. It has also, through the Grand Challenge Chapters, identified critical knowledge gaps that will need to be addressed in the coming decades to provide the necessary understanding of how the ocean and its ecosystems work and interact with other components of the Earth system (atmosphere, biosphere, geosphere). Ultimately, this will allow us to determine how this system responds to and influences an environment which is changing as a result of local anthropogenic drivers and the effects of global climate change. The holistic requirements to address the identified science needs have been detailed in the Grand Challenge Chapters and summarised in Chapter 10. These requirements encompass the variables, samples, and observations to capture; infrastructure, platforms, people and skills required to do so; and new and emerging technologies (e.g. modelling, machine learning) to transfer, store, process, interrogate and synthesise the data.

Supplementing these, a need for developing and maintaining relationships with diverse stakeholders, collaborators and international partners required to do all this in the most efficient, sustainable, and effective manner and over the range of required scales, was identified – ensuring the greatest impact. Further, requirements were identified at the international level, through programmes such as the GOOS and in the Net Zero Oceanographic Capability (NZOC) project, completed in 2022. To ensure that the SRF captures the needs of the UK's diverse marine science community, input from the editors of the NZOC report, scientists with specialist expertise in each of the Grand Challenge Chapters, and the wider marine science community, was sought through a series of consultations and external review (see Appendix).

11.1. Science Capabilities

Here we summarise the recommendations of the SRF in terms of future scientific requirements:

- UK marine science must move from observing changes in the physical, biogeochemical, biological and geological processes within systems to understanding the underlying processes driving responses to enable better predictability of the outcomes of environmental change. The marine realm is recognised as displaying characteristics associated with complex systems including regime shifts, tipping points, state-dependent and emergent behaviours often resulting from non-linear dynamics. Such phenomena require understanding of the relationships among system components at diverse scales of time, space and organizational complexity. For biological systems, in particular, understanding interactions between species, and how this is modified by their responses to the physical and biogeochemical environment as well as anthropogenic stressors, requires modern observational approaches at high spatial and temporal resolution. New modelling approaches, such as trait-based modelling, may be necessary to gain a better understanding of how biodiversity influences ocean biogeochemical cycles and responses to climate change.
- There is an ongoing requirement to expand ocean observations across spatial and temporal scales from microscopic to global and sub-second to multi-decadal. These observations include not only Essential Ocean Variables but also a range of other geological, physical and biogeochemical parameters (see Chapters 4-9). Observations of biological parameters such as species composition, abundance, and biomass of pelagic and benthic communities, as well as biological rate measurements within all these ecosystem components are also required. Observations extend to assessment of multiple human activities in the ocean and the speciation and distribution of pollutants. These requirements cut across major areas of marine science including studying climate, biodiversity, geological hazards and extreme events, pollution and the blue economy.
- Expansion of ocean observations should be achieved at a global level and include the most inaccessible / extreme environments such as the poles, under ice, and the deep-sea and subseafloor, because of the importance of these components of the Earth system to understanding the carbon cycle and the impacts of climate change on the global ocean and its feedback loops. At regional to local scales, high resolution observations are often

required, for example at the open-ocean – shelf – coastal interface, where upscaling of predictive modelling and improved marine spatial planning are needed for sustainable and safe economic development in the coastal zone and offshore shelf seas.

- Understanding the potential physical, biogeochemical and biological responses to climate change, including the nature of tipping points and the risks of exceeding their thresholds, as well as the frequency and magnitude of hazards and extreme events, requires an understanding of the past ocean. This is facilitated through analysis of the geological and biological time machines represented by the physical and chemical composition of sediment cores as well as the skeletal remains of marine organisms such as foraminifera and corals. It also requires understanding of the geology and evolution of the seafloor and subseafloor, from geophysical, seismic, electromagnetic, magnetic and gravity measurements as well as physical sampling of the subseafloor including deep drilling/coring. This would be further strengthened by an understanding of the tectonic evolution of the ocean basins, the connections between them and the changing distributions of the continents, to understand the past boundary conditions to the ocean-climate system.

- Measuring dynamic processes in the ocean is of great importance across the full range of marine sciences. These include measurements of geological, physical, biogeochemical and biological fluxes and rates of key elements, organic and inorganic compounds, including between organisms and the environment, and between organisms that make up a food web. The dynamics influence ecosystem structure and function and alongside the changing environment, influence migratory behaviour and larval dispersal. Spatial and temporal variation in human impacts are also highly relevant, including how pollutants are transported through the ocean, how organisms are exposed to them and the physiological responses that they induce, both singly and in combination. High-resolution marine geology datasets are also needed, particularly in the coastal zone, including monitoring temporal seabed evolution through pre- and post-event data and seabed morphodynamics, to advance hazard management strategies. Measurements of dynamic processes require both 'at sea' observations as well as experimental approaches on board ships, in laboratories or in mesocosms.

- A digital transformation is ongoing in the collection, curation, transmission and storage of scientific (and other) data. The continuation and acceleration of this transformation in the context of marine observing infrastructure will enable opening of access to a wider range of data users and stakeholders. This transition should enable real-time or near real-time transmission of data from science platforms to shore (and vice versa) including the development of more on board or on platform data processing (edge computing). A wider range of data types will require accessible storage, and standardised formats of data and metadata should be adopted at national and international levels to enable tool development and high-speed machine to machine communication.

- A part of the digital transformation is the development of advanced data analysis and predictive tools. These include advanced models (e.g. Digital Twins) and other numerical tools enabled through artificial intelligence, especially for upscaling meteorological and oceanographic forecasting and hazard prediction at the regional to local level, as well as more advanced ocean and Earth system models that, for example, encompass more complexity in biological systems as well as socioeconomic data. The use of machine learning in computer vision applications such as annotation of video data and automated species identification is rapidly developing and should also be supported. These examples of developments in AI represent a digital revolution that likely has applications in all areas of marine science where objective interrogation of a dataset is currently beyond human capability because of size, complexity or processing time. Investments in the digital transformation should consider the whole value chain from data generation, through information to knowledge and understanding.

11.2. Infrastructure Considerations

Here we summarise the recommendations of the SRF in terms of the characteristics that a future infrastructure would require to provide the scientific capabilities summarised above. Noting that overall capacity of the different components of any infrastructure system will also need to be considered alongside capabilities at a subsequent detailed technical solution phase, the following recommendations are made. Given the breadth and depth of different scientific capability requirements across system observable characteristics (e.g. physical, biological, chemical, geological) and scales (multiple orders of magnitude in time and space) highlighted throughout the SRF, any future infrastructure should maintain (and ideally expand on) the UKs current world leading position in terms of versatility and flexibility.

- From an observing platform perspective, many of the science requirements outlined by the SRF can be met through expansion of the autonomous fleet and other remote sensing tools (Whitt et al. 2020). However, the SRF also identifies multiple types of capability (for example: retrieval of large physical samples, development of mechanistic understanding through *in-situ* multi-disciplinary experimentation, geophysical observations, sediment and rock coring, application of multiple complex analytical methods simultaneously), that can only currently, and likely for the foreseeable future, be achieved through the use of oceanographic research vessels (Satterthwaite et al. 2025).

- Observing a wider range of system variables at a wider range of scales requires acceleration in the adoption of multiple new technologies, such as satellite and aerial remote sensing, molecular genetics, computer vision and cable sensing, as well the development of a range of new sensors particularly for deployment on existing and new autonomous platforms. Sensors are required for measurements of physical, biogeochemical, geological and biological parameters as well as for a range of pollutants including radioactive materials. Such sensors need to be robust, modular (i.e. plug and play), validated against existing methodologies and standardised and calibrated, especially where they are used for long-term measurements, and ideally low cost. Ship-board activities will often be a requirement in the development, testing and validation of these new observing systems.

- Digital tools, including ocean modelling and artificial intelligence, will play a significant role in the planning and dynamic control of operational marine science at sea, offering the potential to reduce the CO_2 footprint of vessels and allow adaptation of cruises / missions to changes in the environment.

- Telepresence represents an opportunity to decrease CO_2 footprints and broaden the accessibility of active participation in science at sea to a wider community of scientists and to the public through engagement activities.

- Increased partnership with industry offers a pathway to access industry data, to drive more sustainable practices and to encourage public-private partnership in technology development and commercialisation.

- Other facilities required include national networks of laboratories, facilities to store samples, data and equipment/platforms, and both modelling and data centres. A Hub-and-Spoke development of centres of expertise, for example in biodiversity studies and autonomous technology development, is recommended as a model for facilitating this. These hubs would act as centres of excellence linking to external organisations with specific relevant expertise, as well as supporting the wider marine science community in a particular area of science including through training. Such hubs need not be physical (i.e. could be virtual) and would help to develop a better sense of community at national level amongst scientists distributed across multiple institutions but with common interests. Hubs should strive to emphasise accessibility across the UK science community and different disciplines, with open data access.

- Adoption of new technologies and the digital transformation of marine sciences will require capacity development in areas where there is already competition for skills with industry. There needs to be a coordinated approach in educating/training the marine scientists of the future to be conversant with digital tools, the use of a range of technologies and multidisciplinary approaches to science. Such training will also be required to upskill the existing workforce of scientists (including data scientists), engineers and marine facilities planning staff.

11.3. References

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