PART 1: Strategic Overview and Context

1. Introduction

The UK Science and Technology Framework[1] (2023) highlights that Science and Technology will be the major driver of prosperity this century, noting the need to strengthen partnerships between public, private sectors and civil society, national and international, to realise this this ambition. Marine Science is the perfect example - demanding strong collaborations to better understand the Ocean - a highly connected global system atmosphere to lithosphere, open ocean to coast, physics to fish - providing a great laboratory for innovation and technological development.

UK marine science is innovative and dynamic, with strength and depth across a broad spectrum of ocean topics that have strong links into our marine economy, estimated at £192 Billion in 2014, or 6.1% of total UK economy output[2]. The UK is also internationally respected as a major contributor to climate and biodiversity policy[3], giving us 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 position, alongside the benefits it brings for the UK economy and population, UK marine science now needs strategic investment in its infrastructure and access to physical and digital infrastructure is one of 8 strategic priorities in the UK Science and Technology Framework.

Commented [AS1]: Ref?

The UK Government Chief Scientist's Foresight Future of the Sea Report[4] (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.

[1] UK Science and Technology Framework https://www.gov.uk/government/publications/uk-science-and-technology-framework
[2] Stebbings et al., (2020) The marine economy of the United Kingdom. *Marine Policy* 116 ScienceDirect https://doi.org/10.1016/j.marpol.2020.103905
[3] ...
[4] Foresight Future of the Sea Report (2018) https://www.gov.uk/government/publications/future-of-the-sea--2

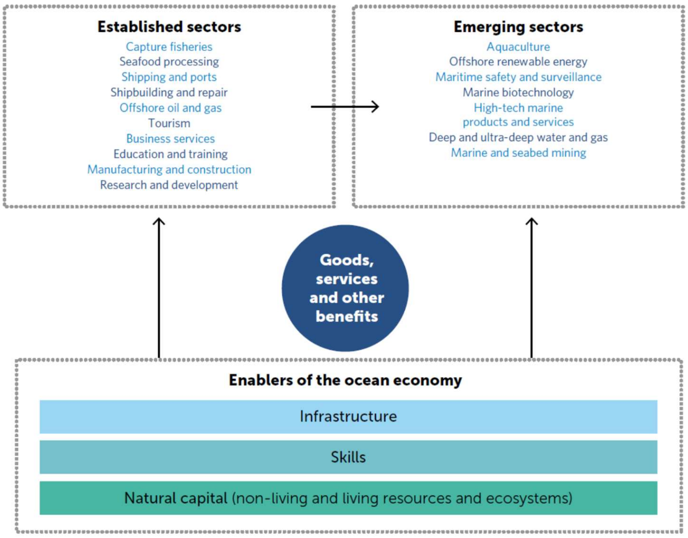

Figure 1.1: The interconnected nature of the blue economy (Foresight Future of the Sea Report).

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[5] 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.

The Natural Environment Research Council (NERC) 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, capitalising on developing technologies and data availability.

[5] UKRI Infrastructure Roadmap https://www.ukri.org/wp-content/uploads/2020/10/UKRI-201020-UKinfrastructure-opportunities-to-grow-our-capacity-FINAL.pdf

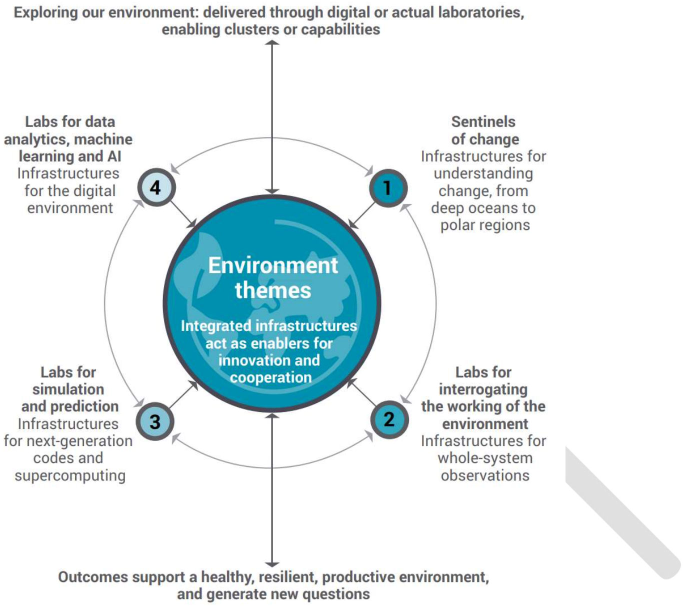

Figure 1.2: Environment sector infrastructure framework (Source: UKRI Infrastructure Roadmap).

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 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[6] greater political and financial uncertainties around the world; the role of understanding the ocean in charting a resilient and sustainable future for all is ever more present. One of the UN Agenda 2030 Sustainable

[6] Navigating New Horizons: A global foresight report on planetary health and human wellbeing (UN Environment Programme) https://www.unep.org/resources/global-foresight-report

Development Goals[7] is focused on the Ocean (SDG 14: Life below water), however ocean science, data and services can be shown to underpin all the SDGs[8].

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.

While other nations are considering how they transition research vessels to green fuels, invest in autonomy and invest in digital infrastructure, FMRI presents an opportunity to take a holistic and forward-looking approach to influence the national landscape positively to maximise science impact and information value for investment in the UK's marine research infrastructure.

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 marine infrastructure portfolio that leads using innovations in measurements and platforms to push the frontiers of marine science,
- An approach that is outward looking and offers global leadership, collaboration opportunities and opening access to under-represented groups.

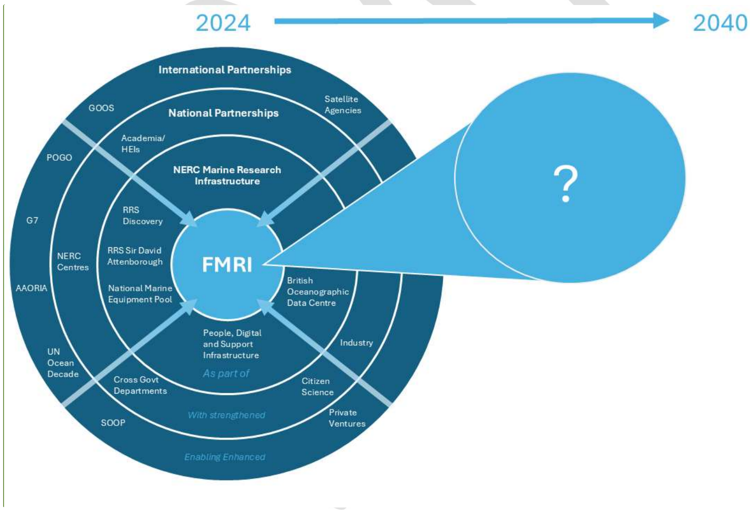

Figure 1.3: FMRI in the context of broader Marine Research Infrastructure <*WORK IN PROGRESS*>

Commented [LU2]: how to thread holistic review across entire capability with specific focus on replacing the JC? how to draw circles around UKRI owned, UK government owned, private/international/commercial

Commented [KH3R2]: Agreed. Needs a diagram! 😊

Commented [KH4]: Definitely a work in progress...>!

Commented [ka5R4]: Again, include citizen science/ships of opportunity in here? Big private ventures e.g., Schmidt Ocean, RevOcean etc.

[7] The UN Agenda 2030 Sustainable Development Goals https://sdgs.un.org/goals
[8] von Schuckmann, K., Holland, E., Haugan, P. and Thomson, P., 2020. Ocean science, data, and services for the UN 2030 Sustainable Development Goals. *Marine Policy*, *121*, p.104154.

1.1. NERC Marine Research Infrastructure

The NERC marine infrastructure can broadly be broken down into five areas (Figure 1.4). Three research ships, two operated by the NOC and one by the British Antarctic Survey. The National Marine Equipment pool which includes mooring and sampling equipment, gliders and AUVs. And a supporting infrastructure and wider research environment, notably including our people. The Focus of FMRI is on scoping next phase investment in Marine Science Capability when NERC's oldest vessel, RRS James Cook, which reaches the end of its nominal 25-year design life in 2031.

Figure 1.4: Illustration of composition of current UK Marine Research Infrastructure under consideration comprising 3 global class research vessels, the national marine equipment pool, data management through the British Oceanographic Data Centre and associated human capability.

Responding to the UKRI's goal to achieve net zero carbon emissions by 2040[9] and with an eye to the planning timelines required to transition our marine research infrastructure, NERC commissioned a scoping study on NZOC[10] in 2020-2021. The NZOC report sought to identify options for developing a world-class oceanographic capability with a reduced carbon footprint by presenting a range of options for transitioning to low or zero carbon capabilities. The scoping study comprised WPs focused on Future Science Needs, Future Policy and Regulation, and packages on Future Ships, Marine Autonomy, Sensors and Digital Environment. Further discussion of NZOC outcomes, and particularly WP1 on future science needs, can be found throughout this document.

1.2. Working towards a vision for Future Marine Research Infrastructure in 2040.

To achieve the full FMRI vision and to meet the goals of the programme, the business case for the replacement capability for RRS James Cook needs to be considered within the wider context of NERC's other marine research infrastructure. While the Marine Science in 2040 document will be used to support the business case to government on the timeline of the replacement capability for the RRS James Cook, the FMRI programme presents an opportunity to take a forward-looking holistic view of future marine science goals. The SRF will inform the Business Case to Government in the context of 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 information value for investment by not just considering investment in

[9] UKRI Sustainability Strategy and Concordat
[10] Net Zero Oceanographic Capability: Executive Summary and Work Package Reports.

Commented [KT6]: This is what we have said, but the options are about the ship and the existing autonomy so I think we need to revise this.

Commented [HKL7R6]: Yes please.

Commented [LU8R6]: we started this discussion previously - the capability we are seeking has multiple aspects: make scientific observations, collect data, share data, train ECRs, test new equipment, soft power, leveraged to enable international partnerships - if we map out the capability rather than the ship then (whilst we've got to mention the ship at some point) we focus upon the capabilities that we are seeking to maintain or enhace

Commented [HKL9R6]: Hello both. This goes back to nailing framing and messaging. Would be good to ensure we are all bought in/on board and we can use and reuse. @Leigh.Storey@nerc.ukri.org - please do edit text accordingly (Note,section 1 may well be a separate info doc, which might be more broadly useful).

Commented [HKL10]: Can we tidy this diagram up a bit. Ensure accurate?

Commented [KH11R10]: We should perhaps include BODC, but noting that is funded separately.

Commented [KH12R10]: I think I want to add BODC?

Commented [KT13R10]: So far we have always had 3x ship, NMEP and underpinning human and digital capability which captures BODC.

Commented [HKL14R10]: OK. I think the Data/Digital bit needs to be more explicit. Have added suggested logo type

Commented [LU15R10]: i'd start with a 'rich picture' that captures the capabilities - introduce the kit later on

Commented [HKL16R10]: @Leigh, suggest text/diagram? (note the framing shown is how the FMRI programme is currently being introduced to the community) 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 and utility of data. This includes:

- Leveraging a range of vessels, including e.g., research vessels, partnerships with other vessel operators and ships of opportunity.
- Considering ‘autonomy’ in its broadest sense, including underway observations, animal tagging, satellite remote sensing, smart 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 broader (non-NERC) infrastructure this sits within, such as future satellite missions, national (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), international partnerships (bilateral partnerships with key strategic partners, and multilateral collaboration through e.g. the Global Ocean Observing System [GOOS], G7 partners).

Commented [ka17]: Yup - see comments above

Commented [KH18R17]: Yup - it's here :-)

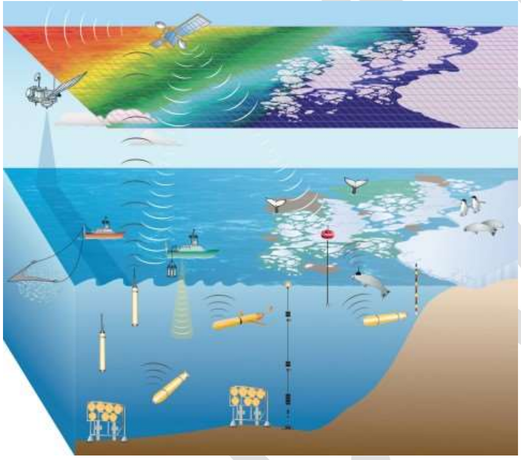

Figure 1.5: (Placeholder - example from SOOS) – vision for a broader integrated capability (with partnerships). Focused on Atlantic, highlighting the role of FMRI investment and partnerships. UK Future Marine Research Infrastructure in 2040.

Commented [KH19]: Working on a version building on this for FMRI (UK Marine Science scope, Atlantic, 2040 focused).

2. UK Marine Science in 2024

In the UK, as an island nation with strong maritime trade and defence interests, the ocean touches all aspects of our lives. It plays a central role in our weather and climate; cities and communities and industries develop along its coast; a frontier for both prosperity and wellbeing as well as for natural hazards. A sustainable future requires a knowledge-based relationship with the ocean. Indeed, as the ocean is a major sink of carbon and excess heat

Commented [mi20]: Perhaps more could be made of govt priorities in here somewhere. e.g.marine-research.pdf (publishing.service.gov.uk) for Defra, and i imagine there will be similar for Scottish Govt. e.g. nature restoration, blue economy, etc.

Commented [KH21R20]: Following up with Defra (main driver mNCEA, discussed below, for Scottish Govt, Mark Innall might advise!).

trapped in the earth system, understanding the ocean and how it is changing is intrinsically linked to achieving planetary net zero emissions.

The footprint of UK Overseas territories and interests have ensured the UK has truly global interests in marine science. The UK plays a proactive part in international ocean affairs, playing a key role in shaping international agreements such as the successful Biodiversity Beyond National Jurisdiction (BBNJ) negotiations, the Antarctic Treaty, and the International Seabed Authority (ISA). All require evidence-based decision making and hence greater observation and understanding of the global ocean.

2.1. Introducing UK Marine Science

The UK is an established leader in Marine Science drawing on a strong and diverse Marine science institutional landscape, comprising:

- NERC Funded Centres: the National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML), British Antarctic Survey (BAS) who are delivery partners for National Capability, plus the Marine Biological Association (MBA).
- Higher Education Institutes: Marine Science has a broad footprint across the UK's academic landscape which is challenging to quantify. While Universities such as Southampton, Liverpool and Plymouth have specific marine science departments or institutes, many more universities are involved in aspects of marine science, e.g. as part of an earth science or ocean policy and governance programme.
- Defra, its arm's length bodies (e.g. Centre for Environment, Fisheries and Aquaculture Science [Cefas]) and marine bodies in devolved administrations.

UK researchers are responsible for 10% of oceanographic and marine geoscience papers and increasing international collaboration over the past 50 years (Mitchell, 2020[11]), which has been supported by the UK's world-class marine research infrastructure and remains one of the top five nations globally in high-quality marine scientific outputs[12].

The UK continues to provide leadership in ocean observing, building on its role in the World Ocean Circulation Experiment in the 80s and 90s, and continues to play a key role in major international programmes. There is a strategic focus on the Atlantic 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, GO-SHIP repeat hydrology lines, etc. Additionally, the UK marine science fields have a broad geographical range from the Arctic to Southern Ocean.

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*

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[11] Michell (2020), Comparing the post-WWII publication histories of oceanography and marine geoscience. *Scientometrics* https://doi.org/10.1007/s11192-020-03498-2
[12] IOC-UNESCO. 2020. *Global Ocean Science Report 2020–Charting Capacity for Ocean Sustainability*. K. Isensee (ed.), Paris, UNESCO Publishing. 245pp. https://gosr.ioc-unesco.org/files/GOSR2020_IOC-UNESCO_full_report.pdf

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."

NZOC WP1 also conducted a survey of usage of the National Marine Facility in recent years, showing a wide range in subject areas but increasing strengths in multidisciplinary research - this UK capability has been featured in European Marine Board (EMB) reports on future research vessels. Also, the NZOC WP1 survey suggested that over 75% of respondents used autonomous tech in their research. From the NZOC literature analysis (Brannigan, 2021[13]), the UK has adapted to using autonomous vehicles much more rapidly than the global average. For example, over the last 5 years, the UK has been publishing results based on gliders at 2-3 times the rate of the global average.

Commented [KH22]: @Kate Hendry: Full ref?

Commented [AS23R22]: Brannigan, L. (2021) Net Zero Oceanographic Capability - Journal and cruise analysis

Commented [24R22]: Hello Alycia, suggest you add the more straightforward changes such as adding references in the text and mark the comment addressed so we can clean up chapters as much as poss :-)

2.2. UK Marine Science Reviews and Strategies

The UK has invested strongly in marine research infrastructure over the years as outlined in the Scanning the Horizon report (2013)[14]. Thus, UK scientists are relatively well equipped to support marine science, with modern multipurpose research vessels and a national marine equipment pool to draw on and investment in 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 highlights that the UKs long-standing record in Marine Science is reliant on research vessels and ship-based equipment as the most reliable and accurate means of carrying out marine science. However, the report noted that the recent expansion in Marine Autonomous Systems (MAS) and Earth Observation (EO) have opened new avenues for research and revolutionised our understanding of the ocean. Key positive disrupters to our observation capability include the Argo array of profiling floats and Satellite Altimetry (most recently swath altimetry). However, the real power is the value that can be extracted by combining these observations (further discussed in section 3). It is anticipated that further step changes will be made into biogeochemistry with the expansion of autonomous observations and sensing capabilities.

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 include:*

- *Deep rock drilling,*
- *Marine ecosystem studies with measurements of rates of production and respiration,*
- *Measurements of isotope systems."*

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

[13] Brannigan, L. (2021) Net Zero Oceanographic Capability - Journal and cruise analysis.
[14] Scanning the Horizon: The future role of research ships and autonomous measurement systems in marine and earth sciences.

measured at the same time and place, enabling maximum value to be extracted from data-streams collected from more autonomous systems. Ensuring delivery of maximum information value for investment in observation capability needs is at the core of the vision for FMRI. Further details of the NZOC recommendations are drawn out in chapters 10, 11 and 12 below.

In 2022, a consultation was held on prioritising UK sustained ocean observations[15]. 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 have been carried forward through this document to help frame requirements for FMRI which comprises both sustained and experimental capabilities. In particular, the science requirements will be framed under marine science 'Grand Challenges' to ensure the societal benefit, purpose and science questions, as well as an integrated cross systems view of observation requirements where contributions of capabilities are clearly articulated.

2.3. Current Marine Science Programmes and priorities

In 2024, some of the major NERC-funded programmes currently underway give an indicator of the status and approach of UK Marine 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 aligned with UK national priorities, leveraging International Programmes and partners to optimise impact of combined investment.

For example, the Atlantic Climate and Environment Strategic Science (AtlantiS[16]) programme is the new National Capability large single-centre 5-year science programme

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[15] UK Sustained Scientific Ocean Observation Priorities (SSOOP) report (2022)
[16] Atlantic Climate and Environment Strategic Science (Atlantis) https://noc.ac.uk/projects/atlantic-climate-environment-strategic-science

which replaces Climate Linked Atlantic Sector Science (CLASS[17]). This comprises underpinning large-scale sustained observations and modelling programmes, technological development, and digital innovation as well as an integrated research programme. The programme is aligned with UKRI and NERC strategies, national and international frameworks, strategies, implementation plans, including UN Ocean Decade, GOOS, IPCC, MCCIP, and the National Adaptation Programme, with a strengthened focus on delivering information to support decision making with a focus on priority knowledge gaps.

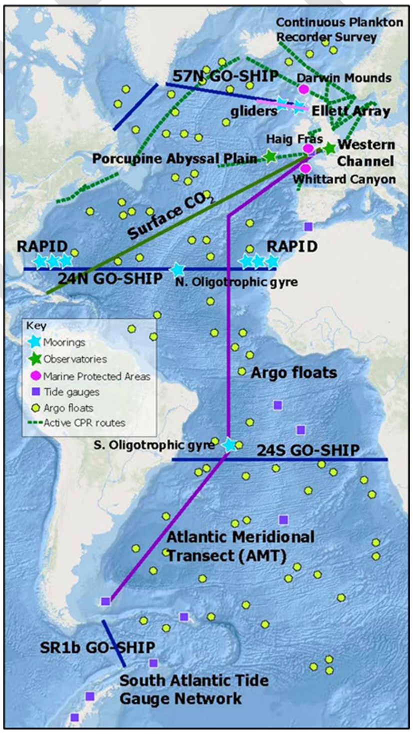
- Theme I: How natural and anthropogenic drivers of basin and decadal changes are altering the Atlantic ecosystem, and the consequences for ecosystem functioning and services.
- Theme II: The importance of ocean-shelf-coast connectivity in shaping ecosystems, biodiversity, natural hazards and impacts on society.
- Theme III: The implications and feedbacks associated with climate mitigation strategies, and the need for improved assessments and advice to policy makers.
- Theme IV: The sensitivity and timescales of feedbacks that determine the ability of the ocean to continue to mitigate climate change by absorbing excess heat and carbon.

The programme is aligned with UKRI and NERC strategies, national and international programmes by design. 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).

Sustained observation components include:

- 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.
- BGC and Deep Argo Float Datasets.
- Underway surface CO_2.



[17] Climate Linked Atlantic Sector Science (CLASS) https://projects.noc.ac.uk/class-project/

Figure 2.1: Sustained Observations within the NC/Atlantis Programme.

Commented [KH25]: Is there an updated version of this for AtlantiS?

Complementary to AtlantiS, two programmes, National Capability Science programme BIOPOLE[18] and the Strategic Priority Programme BIO-Carbon[19], 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 lay down the gauntlet for our research in terms of our ability to measure coincident physics, chemistry and biology observations at a range of spatial and temporal scales, and model complex physical, chemical and biological processes and their interactions (see section 10.4 for more details).

NERC also funds major 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[20] is funded by NERC, the Economic and Social Sciences 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.

Further, NERC programmes such as Examining the Effects of Manmade Structures in the North Sea (INSITE)[21], Ecological Effects of Offshore Wind (ECOFlow)[22], and the new Value of Marine Artificial Structures (ValMAS)[23] programmes are designed to provide the evidence to support marine industries in partnership with industry groups.

Defra's flagship Marine Natural Capital Ecosystem Assessment programme (mNCEA)[24] has brought into sharper focus Defra's evolving requirements for observation and prediction of and metrics on UK marine ecosystems and 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), 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 our observation capabilities of biodiversity in the UK's 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 lead to the publication of a report[25] co-authored between NOC and Defra and informed the FMRI: Accelerating adoption of marine sensor innovation – UKRI[26] competition fund.

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18 BIOPOLE - Biopole
19 BIO-Carbon | National Oceanography Centre
20 Sustainable Management of Marine Resources (SMMR) Programme, www.smmr.org.uk
21 Examining the Effects of Manmade Structures in the North Sea (INSITE) https://insitenorthsea.org/
22 The Ecological Effects of Floating Offshore Wind (ECOFlow) https://www.ecoflow.org.uk/
23 Pre-announcement: Value of Marine Artificial Structures (ValMAS) – UKRI
24 Marine Natural Capital Ecosystem Assessment (mNCEA) https://marinescience.blog.gov.uk/2022/04/13/introducing-the-marine-natural-capital-and-ecosystem-assessment-programme-mncea/
25 https://fmri.ac.uk/sites/fmri/files/documents/measurement-systems-for-21st-century-oceanography-report.pdf
26 UKRI Accelerating the adoption of marine sensors competitive fund: https://www.ukri.org/opportunity/accelerating-adoption-of-marine-sensor-innovation/

In driving the development of innovative digital solutions, Twinning Capability for the Natural Environment (TWINE) is a partnership between the Natural Environment Research Council (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 3 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: which is focused on bringing together climate measurements and models to create an early warning system[27].

Commented [ka26]: Also international opportunities e.g., OBVI/Schimdt Ocean https://www.schmidtsciences.org/the-ocean-biogeochemistry-virtual-institute-obvi/

Commented [KH27R26]: @Alex Rogers unpack science funded through Philanthropy (Schmidt, REVOcean, OceanCensus, etc).

2.4. Expected future priorities for Marine Science.

Looking to the future, while NERC is coming to the end of its current strategic planning period, NERC will likely continue to reinforce a focus on science for solutions for society. NERC's Strategic Delivery Plan 2022-2025[28] 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, working in partnership with other research councils, government and industry partners are expected to grow as priorities into the future, e.g. UK National Climate Science Partnership[29], a collaboration between the NERC funded centres and the UK Met Office. This direction reinforces the need to consider FMRI in the wider national partnerships landscape.

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

27 ARIA-Forecasting-Climate-Tipping-Points-Programme-Thesis.pdf
28 NERC Strategic Delivery Plan 2022-25
29 UK National Climate Science Partnership https://www.metoffice.gov.uk/research/approach/collaboration/uk-national-climate-science-partnership

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[30] provides a strong foundation to guide the development of FMRI's Digital Infrastructure.

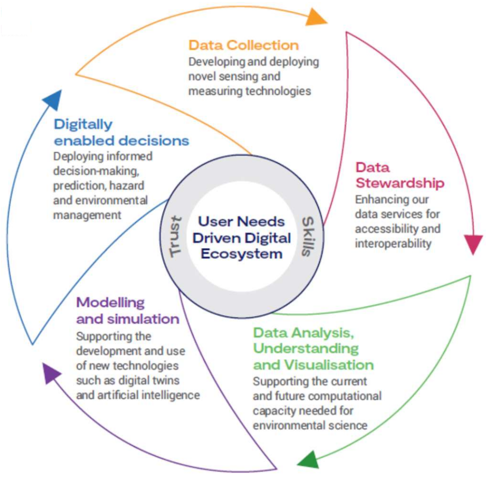

Figure 2.2: NERC's proposed Digital Ecosystem approach bringing together data collection, data stewardship, analysis understanding and visualisation, modelling and simulation for digitally enabled decisions.

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

- World Class Science for solutions and society,
- Uniting observations and digital tools,
- Working in partnership.

3. Global developments and international best practice.

The Ocean is a complex and highly connected global system where physics, chemistry and biology intersect at all scales, touching on all aspects of our lives from the weather we experience to the food we eat. While the UK can spin up large scale observation and research programmes, no single nation can measure all aspects of the ocean 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.

[30] NERC Digital Strategy 2021-2030

3.1. The Global Ocean Observing System

The UN's GOOS is sponsored by the World Meteorological Organisation, Intergovernmental Oceanographic Commission, UN Environment Programme and the International Science Council. GOOS communicates the case and requirements for sustained ocean observations through the UN system to member states, evaluates requirements for sustained ocean observations through internationally agreed Essential Ocean Variables (EOVs) and reviews implementation through globally coordinated networks.

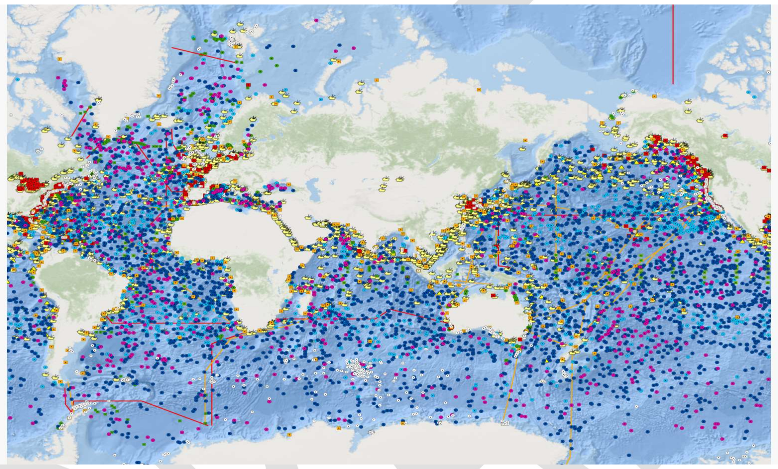

Figure 3.1: Schematic of the Global Ocean Observing System (Source: www.ocean-ops.org)

The original GOOS design was motivated largely by the need to deliver to Climate and developed in collaboration with the UN Global Climate Observing System (GCOS)[31], which then agreed Essential Climate Variables (ECVs). GCOS submits Implementation Plans[32] to the UN Framework Convention on Climate Change which provides a legal framework to request member states to measure ECVs[33]. The GCOS monitoring principles[34] 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. The framework identified the need to articulate requirements for the observing system using 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.

[31] WMO-IOC-UNEP-ISC Global Climate Observing System (GCOS)
[32] GCOS Implementation Plan 2022
[33] UNFCCC - Research and Systematic Observations
[34] GCOS Monitoring Principles https://gcos.wmo.int/en/essential-climate-variables/about/gcos-monitoring-principles

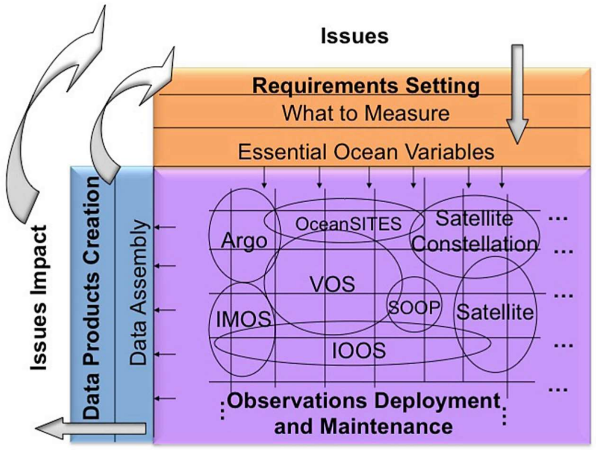

*Figure 3.2: Introducing a Framework for Ocean Observing, shaped by requirements. **"Structure of the Framework for Ocean Observing.** How ocean observing activities fit into the systems model of the Framework. The critical feedback loop between observing system outputs and science-driven requirements 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), GOOS agreed a set of EOVs which should be observed globally, with requirements specified (

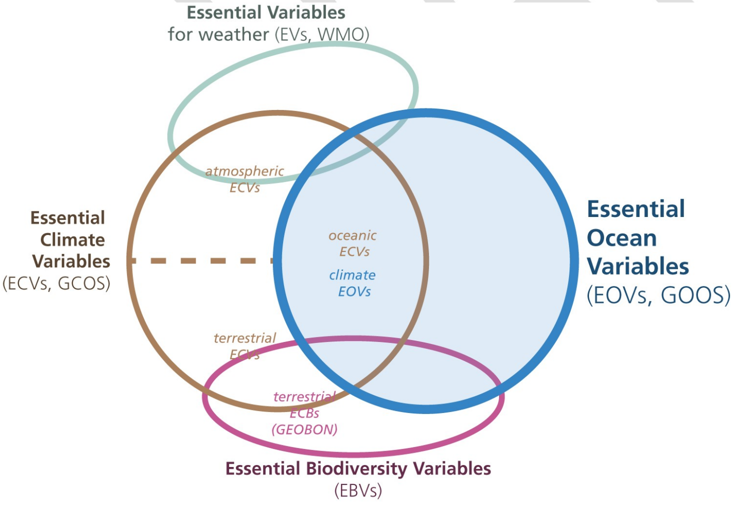

Figure 3.3). These are driven by requirements, negotiated with feasibility – recognising we cannot measure everything, nor do we need to. EOVs provide the basis for including new elements of the system, for expressing requirements at a high level, allowing for innovation in the observing system over time. The EOVs will be discussed further in chapter 11, the synthesis of requirements.

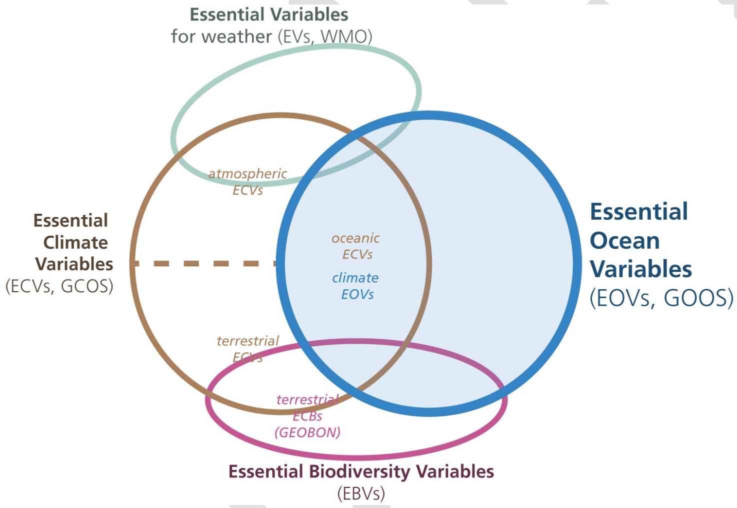

Figure 3.3: Essential Ocean Variables and relationship with other variable requirements.

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. Something considered in depth during the Tropical Pacific Observing System, 2020 project[35], leading to the following definitions:

a) *“**Sustained observations** are defined as measurements taken routinely that [observing system programmes] have committed to on an ongoing basis, generally for seven years or more. These measurements are primarily for public good services or for research in the public interest but will usually support both.*
b) ***Experimental observations** are defined as measurements taken for a limited observing period, generally seven years or less, that observing system programmes are committed to for research and development purposes. These measurements serve to advance knowledge, explore technical innovation and/or lead to improvements in the effectiveness and efficiency of [observing system programmes].” This includes baseline studies, process studies/experiments and pilot projects/studies.*

3.1.1. 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[36] 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”.* 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. This will require strengthened partnerships at national and international levels.

Figure 3.4: 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

[35] Source: TPOS 2020 1st Report. www.tropicalpacific.org
[36] Global Ocean Observing System (GOOS) 2030 Strategy

Decade identified 10 Decade Challenges[37] - three of which are infrastructure challenges (in bold), focused on strengthening observational, digital and human capabilities.

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 3.5). 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 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[38].

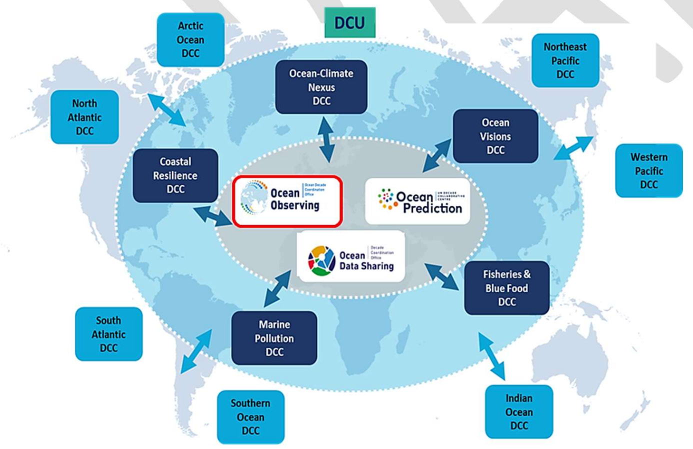

Figure 3.5: Coordination of the UN Ocean Decade: Comprising the Decade Coordination Unit (DCU), Coordination Offices (DCOs) and Collaborative Centres (DCC), with coordination of Ocean Observations, Data and Prediction at its core.

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[37] UN Decade of Ocean Science for Sustainable Development – 10 Decade Challenges
[38] Ambition, Action, Impact: UN Ocean Decade Pathway to 2030 https://oceandecade.org/publications/ambition-action-impact-the-ocean-decade-pathway-to-2030-consolidated-outcomes-of-the-vision-2030-process/

UN Ocean Decade Challenges and Decade Actions as well as relevant international research programmes will be discussed further in section 5, Marine Science in 2040, and in the context of the Marine Science Grand Challenges below.

Building on the UN Ocean Decade and the broader UN Agenda 2030 (Sustainable development goals), the recent EMB 'Navigating the Future' policy brief[39] positions ocean science at the centre of the wider earth system and highlighting the crucial role the Ocean plays in Earth's interconnected systems and outlines a vision for future marine research and policy. Organised around 4 key themes – People, Climate, Freshwater and Biodiversity – the paper called for more calls for more 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 3.6).

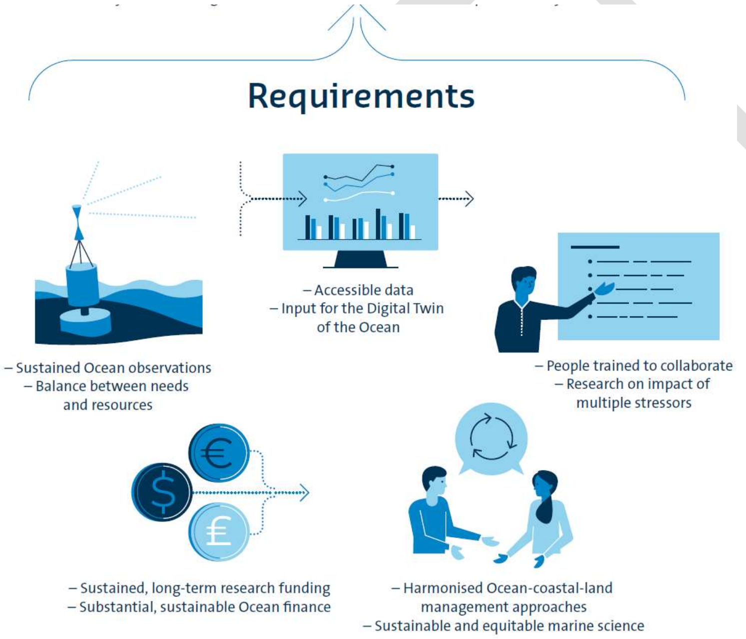

Figure 3.6: Cross cutting requirements for future marine research identified in the European Marine Board 'Navigating the Future IV' Policy Brief[34].

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

[39] European Marine Board 'Navigating the Future IV' Policy Brief - Placing the Ocean within the Wider Earth System https://www.marineboard.eu/publications/nfvi

The International Ocean Discovery Programme (IODP) has developed a new Science Framework for 2050[40] with a focus on 6 strategic priorities which are similar in nature to the 10 Decade Challenges:

- Habitability and Life on Earth,
- Ocean Life Cycle of Tectonic Plates,
- Earth's Climate System,
- Feedbacks in the Earth System,
- Tipping Points in Earth's History,
- Natural Hazards Impacting Society.

The reduction in drilling ship capability globally has impacted the IODP, and the community are exploring how to make use of existing core data e.g. through Artificial Intelligence (AI)/Machine Learning (ML) techniques, insights from other data sources while enhancing the international partnerships required to target and prioritise coring – e.g. with the Japanese drilling vessel.

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. Specific connections to International Programmes will be picked up through section 5 where relevant to the Marine Science Grand Challenges.

Commented [KH28]: Will consider how to develop this relative to international links highlighted through the Grand Challenges.

[40] IODP 2050 Science Framework: Exploring Earth by Scientific Ocean Drilling https://www.iodp.org/2050-science-framework