FUTURE MARINE RESEARCH INFRASTRUCTURE

Measurement Systems for 21st Century Oceanography

Engagement Outcomes

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National Oceanography Centre

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Measurement Systems for 21st Century Oceanography Consultation

Development priorities for biogeochemical and biological measurements for Future Marine Research Infrastructure

Foreword

There is an imperative to measure the ocean in ever greater detail if we are to chart a sustainable future because “the ocean holds the keys to an equitable and sustainable planet” (UN Decade of Ocean Science for Sustainable Development). Marine research infrastructure that is cutting edge, resilient to changes in the ocean system and reliable is a critical enabler. In addition, the point is well made in this report that the infrastructure must also be responsive to future user requirements. Similar reports have also highlighted the requirement for technologies to be standardised, affordable and as simple as possible. All of this is true and advanced sensor technology is the key to unlocking all of it.

Understanding which new sensors should be prioritised alongside which ones might become available over the coming decade allows us to make informed, strategic decisions about how we can best support the UK’s marine science community. If we want to meet the high ambitions set by that community then the technology must also support international collaboration to ensure we retain our leading position in this global endeavour. And the development of this technology has the potential to translate into improved UK economic performance alongside informing policy that promotes the health and security of our coastal communities and overseas territories.

Finally, I believe there already are ‘hero’ scientists and pioneering groups who are dedicated to advancing our understanding the ocean using these new technologies – ‘twas ever thus. But this report is right to advocate strongly for a significant investment in training for all of those involved: scientists, engineers, technicians etc. A transition of this nature requires more effort from more people, not fewer, during the transition: to believe this can be a ‘lean’ process is to invite failure.

I want to thank all of those who contributed to this report but particularly recognise the main authors whose expertise, and generosity with that expert knowledge, guided this activity from start to finish.

Leigh Storey, FMRI Senior Responsible Owner

Introduction

The Future Marine Research Infrastructure programme aims to develop and deliver NERC's strategic investment in the next generation of large-scale, marine research infrastructure. The programme is currently in the business case development phase and is considering how developments in marine sensor technologies might shape the UK's future research infrastructure.

To inform this process, in late 2023 the programme sponsored an engagement exercise with developers, operators, suppliers and users of marine sensors to explore the development priorities for biogeochemical (BGC) and biological measurement systems. Building on the findings of the Net-Zero Oceanographic Capability Scoping Study (NZOC, 2021), the goal was to synthesize expert knowledge and views into recommendations to inform the decisions for a strategic investment in future research infrastructure. This report summarises the goals, discussions, findings, recommendations and conclusions resulting. Note that references to specific sensors and sensor manufacturers reflect the discussions in the workshop and are not intended to inform procurement decisions.

The FMRI programme is exploring different operating models for the future infrastructure. This engagement includes an emphasis on the option of upscaling autonomous observations as this will only prove viable if users have access to in-situ observations for the parameters required and at sufficient levels of precision and accuracy. As identified in the NZOC Scoping Study, a successful transformation of the UK's research capabilities will depend upon accelerating the development of marine sensors, instruments and samplers for an increased range of observations.

In this engagement, specific recommendations were sought for:

- Identification of gaps in current capability both in biogeochemical and biological measurements.
- Opportunities for addressing those gaps.
- Implications for autonomous platforms and systems (including all non-ship platforms) because of the changing landscape of biogeochemical and biological observation technology and the opportunities for less reliance on research ships in elements of the ocean observing capability.
- Wider implications for the oceanographic and marine technology field and community (including: data, skills, collaborations, organizational structures, communication / coordination).

Summary against each of the discussion session topics

What are the key gaps in biological measurements and what might be available in 5 or 10 years?

Identifying key gaps in biological measurements is an essential step in enabling the transition of ship-based capabilities to autonomous platforms. This transition has the potential to significantly reduce the carbon costs of data collection while providing new scientific opportunities through increasing the spatiotemporal resolution of data.

The ability to collect physical samples for biological measurements is a prominent gap. This includes a range of physical sample types including water, sediment, and organisms themselves. Physical sample collection is an important enabler of certain biological measurements, for example pathology, diet, or studying infauna. Similarly, the ability to perform in-situ incubations and experiments was highlighted as a gap. This is important for rate-based measurements and behavioural studies.

Acoustic sensing, both passive and active, was highlighted as an area of significant future potential. This included consideration of how machine learning techniques can be applied to process large volumes of both passive and active acoustic data to inform biological research questions, and how acoustic sensing can be used in combination with other techniques including eDNA.

The further development of eDNA technologies, including the use of qPCR to develop more quantitative insights and the use of RNA to present a more constrained view of presence or metabolic activity, is an area of high potential. This is coupled with rapid advances in sequencing technologies and reductions in costs.

Imagery was highlighted as an area of significant potential across a range of context and scales. Hyperspectral satellite imagery will advance studies of plankton communities across large spatial scales. Benthic imagery may be advanced through developments in imaging platforms, imagery processing capabilities reliant on robust underlying digital infrastructure and reference libraries, and capabilities to process imagery data onboard autonomous platforms to reduce transmission burdens.

Gaps were also identified in microbiology including extracellular production, bacterial measurement including diversity, virology and real time identification of all microbiology. Invasive species were also seen as poorly addressed with autonomy. This could be addressed with sampling, in-situ a priory gene detection, or sequencing. Benthic / Benthos / Infaunal biology were also seen as gaps in autonomous and low carbon approaches. Plankton imaging systems covering the full-size spectra of plankton were seen as gaps, and marrying imaging systems with genetics would move this field forward.

Finally, significant developments in in-situ sampling technologies could occur over the next 5-10 years. This includes in-situ incubators which can facilitate rates and behavioural experiments, and in-situ flow-cytometry, and in-situ sequencing.

Additional input included the need to effectively measure the size and biomass of organisms, developing organism tracking and tagging capabilities (including through autonomous platforms), and advancing sensors for detecting jellyfish and gelatinous zooplankton.

Key Finding 1.1 Autonomous capabilities need to address the gap of physical sample collection, including water, sediment, and organisms.

Key Finding 1.2 eDNA, acoustic sensing, and imagery are focal technologies for further development over the next 5-10 years.

Key Finding 1.3 Clear structures are required to capture and be responsive to evolving user needs and priorities.

What are the key gaps in BGC measurements and what might be available in 5 or 10 years?

The priority order of BGC measurements broadly matched that of the EOV / Framework for Ocean Observation, at least for the top 4 i.e. in this order Oxygen, Carbonate system, Nutrients, Particulates. The community also asked for more process-based study parameters and capability (see full list below). Oxygen was seen as well addressed by current technology, but even there, shortcomings in calibration, accuracy and ease of use were identified. All other sensors were seen as non-optimal and in need of development by most attendees. Therefore, all BGC measurements were seen as a gap by most participants.

There was a consistent call for establishing an open (collaborative) dynamic and regularly updated roadmap for BGC measurement systems including by variable with use case / phenomena and different platforms. It was asked if the WMO rolling requirements review inspires a suggested structure for ensuring future measurement systems are responding to the user community's requirements? [The Rolling Review of Requirements process (2023 update) | World Meteorological Organization (wmo.int)]

Currently, and likely in the 5-10 year horizon, biofouling was seen as a problematic and generic issue that needs management, though some sensors have evidence of overcoming biofouling.

Because of the lack of confidence in BGC sensors, and because of the large number of BGC variables required by users, the development of BGC compatible water sampler technology was seen as a priority by most participants (this is consistent with similar demands for biology). This was seen as feasible in a 5-year horizon and should address:

- Multiple samples from non-ship systems
- Differing requirements / versions or one version that can be configured to do all of:
    - Trace metal,
    - Gas tight,
    - In-situ preservation,
    - Nutrients,
    - Carbonate.

Participants evaluated the following sensors (including many that are available commercially) as priorities yet marginal or just adequate for some studies, but generally in need of improvement. Many sited reliability, accuracy, longevity as key concerns whilst a smaller number of participants sited measurement speed as limiting. Improved sampling rate was seen as necessary for some existing sensors especially on fast moving platforms and in regions of high gradients / when profiling. It was suggested that with focused development and community engagement in that process, these sensors could have sufficient capability within a 5 year horizon.

- pH (ISFET supply issues, robustness for others)
- Alkalinity (in situ)
- pCO2 flux in surface ocean (a gap particularly in the Southern Hemisphere)
- Macronutrient sensors (Nitrate, Phosphate, Silicate (Silicic Acid))
- State measurements in own right, and at sufficient resolution to infer / model rates above
- Sensors for air-sea flux,
- Particulate flux (POC and PIC flux)
- Methane
- Primary productivity (Chelsea Technologies STAF technology)

The following were assessed as being priorities yet much less mature requiring development in a 5-10 year horizon, or more concerted effort if the capability was to be accelerated.

- Dissolved Inorganic Carbon (DIC)
- Air sea flux (gases other than CO2)
- Rate measurements, particularly those in models (e.g. ERSEM includes Primary Productivity; Nutrient uptake and remineralization; carbon uptake and exchange; phytoplankton respiration and photosynthesis; microbial respiration, nutrient and carbon exchange; grazing; filter feeding; particulate settling; dissolved organic matter flux; benthic and surface fluxes etc. etc.)
- Rate measurements and experimental (perturbation) manipulations are key to many process studies but currently difficult without crewed vessels.
- Low level trace metals including:
    - Mercury (Hg)
    - Chromium
    - Copper
- Low level (oligotrophic waters) nutrients ~nM resolution and accuracy
- Isotopes
- Elements in particles including PIC, POC, PON, POP
- DOM and DO nutrients
- Fe (II and III)
- Ammonium (particularly at low concentrations / surface ocean / oligotrophic)
- Nitrous Oxide
- Persistent Organic Pollutants
- Organic Geochemistry
- Iodine
- Microplastics
- Pigments (other than chlorophyll)

To address user experience of sensor drift and problematic accuracy, many participants recommended that systems for in-situ calibration be developed / incorporated in BGC measurement systems. Currently this is frequently done using climatology (e.g. known and well constrained chemistry in deep waters, the surface ocean, or in areas recently measured with trusted / traditional techniques), though a desire for alternative methods (such as onboard standards) was expressed. This could be particularly useful for dynamic environments where there is no stable climatology to use as a calibration.

Most participants highlighted the need for synoptic and coincident observations of other parameters e.g. physics and biology to provide and ensemble of measurements enabling characterization or modelling of the ecosystem / process under study.

It was widely accepted that there was a need to extend low-carbon platforms, sensing and sampling into the sediments, coast, near shore and estuaries.

Conclusions

1. There was widespread demand for an open (collaborative) dynamic and regularly updated roadmap for BGC measurement systems including by variable with use case / phenomena and different platforms. This echoes Key Finding 1.3 for biological measurements above.
2. The community felt most if not all BGC sensors were immature and had limiting problems, and for many parameters did not yet exist. They requested greater engagement with users in the development of the technologies, and significant overlap where existing / traditional methods are deployed alongside the new approaches. This secures long term data sets, enables improvement of the technology, and builds user trust.
3. The UK community has a greater emphasis on process studies which necessitates more capable and diverse measurement capability (than an operational global observing system for example) such as samplers, incubators and the ability to make experiments or interventions (both to samples in situ or more generally in the environment). Beyond this requirement the community prioritizations closely matched those present in the EOV / FOO framework but with some users emphasizing multiple synoptic or ensemble measurements (multiple parameters recorded simultaneously).

Key Finding 2.1 There is a demand for a collaborative, dynamic and regularly updated roadmap for BGC measurement systems.

Key Finding 2.2 There is a need for greater engagement with users in the development of the technologies and for building trust in new technologies.

Key Finding 2.3 UK science requirements necessitate diverse measurement capabilities such as samplers, incubators and the ability to make experiments or interventions.

What are the options for advancing the identified measurement priorities?

A roadmap should be developed to underpin sensor and platform development. This should include comprehensive capture of requirements by user group, rolling gap analysis and requirements review, and a clear process for sensor/platform development in partnership with users from inception through evaluation to widespread application.

Appropriate funding models must be applied to establish sustained programme infrastructure, including coordination structures, working groups, support for champions (e.g. science users) pioneering applications, and managing cross-organisation equipment catalogues to accompany project-based funding.

Sensors must be tested prior to deployment across their range of operational environments (e.g. temperature gradients) and at scale, as once deployed sensors may be difficult or costly to recover. This should be supported by stronger collaboration between industry and end-users. Furthermore, projects focused on testing and validating sensors in parallel with existing methods should be prioritised and supported. Such an overlap would build confidence in the community and would help ensure continuity of key datasets whilst the new technology was proven to deliver data of a sufficient quantity.

Similarly, projects on approaches to in-situ sensor calibration should be considered. Carbon cost savings of sensor deployments on autonomous platforms may be undermined if teams need to travel with equipment to perform calibration, or if ship-based measurements are necessary to create climatologies.

International collaboration opportunities should be identified, to reduce duplication, promote interoperability, coalesce priorities, and develop quality control standards allowing progress to be accelerated.

Additional input included consideration of biofouling management for autonomous platforms, ensuring clear data management pathways are established, and securing the traceability to measurements back to specific sensors through metadata.

Some participants questioned if it is pragmatic / optimal to offer “standard fit” of sensors for different platforms?

- This could evolve over time with stakeholder input, and with technology progress
- could highlight gaps for purchasing or focused development
- Would provide a first pass of what we can currently achieve with limited budgets

An initial standard fit could include: CTD, O_2, carbonate system, nutrients, chlorophyll / pigments, primary productivity, particles, imaging systems, and eDNA sampler with selected systems depending on application and platform payload capability with further systems added as directed by the community. A priority is likely to be to respond to the UK community focus on process studies and the need for experimental / incubation / intervention capability.

Conclusions

1. Develop a clear and visible roadmap for sensor / sampler / incubator-manipulator development, supported by appropriate sustained infrastructure and funding. The UK community has a strong focus on process studies and innovation, which requires additional capability (e.g. incubators) beyond the priorities of the EOV framework, though that is nonetheless represented in the community’s prioritization of parameters.
2. Strengthen collaboration between industry, sensor developers and end-users to enable them work together closely and iteratively throughout to ensure needs are met.

3. Sensors should be tested at scale and across their range of operating environments (e.g. depth and temperature) both with the user community, and by an independent evaluating group. This process could begin with the most mature sensors using a “standard fit” of sensors for designated platforms, and then adding technologies as they emerge from actions described from 1 and 2 above.

Key Finding 3.1 Develop a clear and visible roadmap for sensor / sampler development, supported by appropriate sustained infrastructure and funding.

Key Finding 3.2 Strengthen collaboration between industry, sensor developers and end-users to enable them work together closely and iteratively throughout to ensure needs are met.

Key Finding 3.3 Testing of sensors at scale and across their range of operating environments, both with the user community and by an independent evaluating group.

What are the implications for autonomous platform design, use and data management?

Many BGC and biological measurements currently require significant power and payload, and even where miniaturising is progressing, the requirement for synoptic measurement of multiple parameters results in sizeable sensor packages. Existing autonomous platforms have in most part been developed for physical sensing, where the standard CTD is both low-power and small. Imaging and sonar systems, and their integrations with platforms are perhaps a better analogy of what to expect. An alternative is to have multiple vehicles each carrying different measurement systems but working together.

For widespread application of low-carbon approaches / platforms will be needed to deal with coastal and near shore, rugged terrain, under ice operations, and to work near and interacting with sediment / benthos / infaunal communities. The pelagic and standoff benthic operations are easy in comparison.

Several participants highlighted that low-carbon platforms include a wide variety (e.g. moorings, floats, drifters, profilers, tagged animals) and not just the vehicles currently supported by the NMEP. For example, neither bio-Argo nor EMSO/Oceansites are managed within the NMEP. This needs to be considered in the development and evolution of a capability matching user requirements. It was suggested that we re-examine the use of deployment on non-science infrastructure including:

- Cables and pipelines
- Offshore structures
- Aquaculture
- Commercial shipping – can improved technology reduce technical support to make this viable long term?

It was also questioned if any future platforms should be expendable (e.g. Argo) or does greening require recovery of all assets?

The regulator landscape may make some biological / BGC observations difficult – e.g. surface fluxes (surface platforms), or use of toxic or hazardous substances in the measurements / biofouling mitigation. It may have implications for current approaches, e.g. the expendability of (bio-)Argo profiling floats.

Cultural and technological change is needed to reduce carbon from operations of off-ship observing systems including moorings, floats and motile autonomy (all classes) because many systems rely on carbon intensive ship-based deployment.

Because of larger BGC and biology payloads, larger platforms may be required. Design studies need to examine space and power requirements with expanded biology and biochemical fits.

To reap the carbon dividend from a move to increased non-ship systems requires an operational change to reduced personnel travel (smaller and local / in country teams could be used). Shipping of measurement systems close to study area for shore launch as well as greater use of rechargeable rather than primary batteries maximises carbon savings. Without these measures carbon benefits may be limited.

Several participants noted that two-way communications would enable enhanced data from sensor enabled platforms and additional functionality including:

- Edge computing / processing of data to compress telemetered data / info (e.g. AI/ML for imaging)
- Real-time data or at least sensor to platform comms for delayed mode uplink
- Data enables users so that they can re-task measurements / missions.
- Data enables operators to spot faults and optimize operations

When considering autonomous or lean crewed surface vessels a number of participants proposed the use / development of autonomous winch systems. These could be used to autonomously collect samples (pelagic and benthic). An automated system of demounting samples and storage could enable the winch system to collect multiple samples as is done on fully crewed vessels. Sensors could be integrated into sampling packages, and possibly swapped / refreshed using the automated sample handling system. In extremis samples could be processed in an automated onboard laboratory. There were calls for coordinated networks of USVs, perhaps linked to airseaobs – OASIS and for the development of an international USV network c.f. Argo.

Data management was highlighted as a priority by many participants. The development of appropriate and capable data systems will need parallel development to measurement systems and low-carbon platform development. Highlighted priorities included:

- Use of standard vocabularies and metadata best practice to ease automated data ingestion and processing, as well as the FAIR principles (findability, accessibility, interoperability, and reusability)
- The need for translators as single standards and globally agree vocabularies remain illusive
- The need for both measurement technology and data management approaches to support federated data systems, i.e. linked but separate data repositories
- That measurement system developers need to work alongside data professionals to design data flows and data processing (e.g. automated and near real time QC)

Conclusions

1. Low-carbon platforms will need larger payloads, and likely power, to carry BGC and biology measurement systems or will need to work collaboratively carrying different sensors /samplers to enable synoptic measurements of multiple parameters.
2. Edge computing and two-way communication will improve data sets through re-tasking and error management of BGC and biology measurement system carrying assets.
3. Data management will need to be developed in parallel to upscaling of BGC and biology measurement systems. This should focus on FAIR principles, automated ingestion and processing, support for federation and translation including of standard vocabularies. This should be completed in partnership with measurement system developers and users from the outset.

Key Finding 4.1 There is a demand for low-carbon platforms able to support larger and higher power payloads or to operate as networked swarms.

Key Finding 4.2 Edge computing and two-way communication will improve data sets through re-tasking and error management.

Key Finding 4.3 There is a need for parallel development of data management in partnership with measurement system developers and users.

Other topics and themes highlighted

Participants highlighted the need for a concerted effort to highlight the advantages of low-carbon observing with enhanced BGC and biology measurement systems to user communities and stakeholders. I.e. we should sell “the prize” to maximise uptake and achievements by the community. This should socialise applications and capability enabled that cannot be done with traditional methods. This could be done perhaps via working groups to discover and develop opportunities and optimized observing capability design.

There was strong support for investment in people to support and deliver the change including:

- Technology champions / leaders,
- Instrumentation development engineers, technical staff,
- Data and platform developers / specialists,
- multidisciplinary science / application / technology skills,
- ‘Hero’ scientists who will partner with technologist through difficult development years,
- ‘Pioneer’ and early adopter scientists / groups,
- Operational support personnel.

The participants expressed the need to maximise the availability / accessibility of the new ocean capability including a focus on:

- Sustainability:

  - Active management of marine equipment (e.g. NMEP) including retirement to ensure fit to science need / drivers. Can this be expanded to a national catalogue for all potential providers (e.g. HEI and private sector) which has better than current visibility?
  - Development and maintenance of appropriately skilled workforce.
  - Structure and roadmap.
  - Funding.
  - Support infrastructure / services.
- Delivery model – e.g. will a data as a service be commissioned, or will the community have lease, owned capability?
- How will cost / size drivers constrain the types and numbers of platforms and measurement systems?
- Enhanced measurement system longevity as a means to address cost and carbon cost, but may be difficult to achieve for BGC and biology measurements (many require regular replenishment and servicing etc.).
- Participants recognised the reality of current silos for different platforms and different applications and that access is not the same for each currently.

There was consensus around the need for independent review of measurement system TRL and fit to requirement. The community was keen to participate in this including gaining experience for developers and users alike with "at sea" trials. Honest sensor / measurement system evaluation in field conditions is vital for user buy in and to provide feedback for further development / improvement / bug fixing of the technology. However, there was also a call for fully independent testing e.g. working with or c.f. Alliance for Coastal Technologies: Alliance for Coastal Technologies (act-us.info) but focused on autonomous / low-carbon requirement.

A need was strongly expressed for significant overlap of new and existing (e.g. ship and sampling based) methods to demonstrate performance and reliability and to ensure continuity of data sets.

It was suggested to leverage existing infrastructure/lessons learned from established networks (e.g. Argo, Oceansites) as this would lead to efficiencies / more rapid development and take-up. There is a significant international community that UK efforts can be coordinated with e.g. NOAA, the EU ERICs as well as larger projects e.g. GEORGE, EuroSea and its descendants. Equally it was noted that individual labs had developed niche and key measurement capabilities, and if they were given access to support from engineers and sensor developer professionals, these capabilities could be replicated / upscaled and made available to the community through the capability.

The new capability should make maximum use of and contribute to agreed standards and best practice for all aspects (from sensor design to data management). It was recommended to use of the OBPS OBPS – Ocean Best Practices System – Ocean Best Practices System. Development and documentation of standard interfaces for example was seen as a way to reduced development and integration effort.

Participants suggested that the technology development underpinning the roadmap to address users needs should consider a staged development. This could select platforms and applications that would be easier to achieve for early demonstrations (e.g. short deployments, larger platform, more benign conditions) and then test and develop for increasingly difficulty (together with stakeholders / users). For example, there were persistent calls for operations year round in the polar regions and it may be pragmatic to develop for this requirement but to build up to such deployments through a sequence of increasingly challenging deployments.

There was a persistent if not universal request to retain research ship capacity near or at current levels with attendees citing:

- Potential of novel fuels and carbon efficient manufacturing to reduce carbon emissions
- Flexibility and capability of research ships
- The serendipitous interactions by the community developed on a research expedition

Conclusions

1. It was recommended to make a concerted effort to highlight the advantages of low-carbon observing with enhanced BGC and biology measurement systems to user communities and stakeholders to “sell the prize”
2. There should be careful investment in sustainability of the ocean capability including investment in people to ensure the availability of appropriate skills.
3. That development and testing should be taken with the user community, overlapping with traditional methods. This should leverage and add to best practice (e.g. OBPS) and collaborate with / learn lessons from, the international community (e.g. NOAA, EU ERICs, international projects) and existing ocean observations networks e.g. Argo, Oceansites, EMSO and EGO. Testing should build ever increasing challenge to the technology through progressively harder applications, leading up to demonstrations in the world’s most challenging environments such as year-round operations in polar environments.

Key Finding 5.1 A concerted effort is required to highlight the advantages of the future research infrastructure.

Key Finding 5.2 Careful investment is required in people and skills to ensure a sustainable research infrastructure.

Key Finding 5.3 Development and testing needs to be a joint endeavour with the user community, taking the time to build trust in new technologies and new techniques.

Key Conclusions

The workshop generated significant input across priority areas. In both biogeochemistry and biology a consistent message was that many (and perhaps most) current measurement systems that can be used on autonomy fall significantly short of desired capability with key weakness seen as the inability to measure key variables, accuracy, longevity and frequency of measurement. However, there was enthusiasm for achieving the ambitions of a BGC and biology enabled low-carbon observing system as it could also enable new science and applications when developed.

Stakeholders expressed the need to have scientists engaged with the development of measurement systems, for resulting technologies to be developed together with extensive field deployment with the community, and when appropriate the technologies should be independently evaluated by a third party. As for the priority of measuring individual parameters no simple picture emerged: there was a consistent call for enabling process-based studies (with example incubation and experimental / interventional capability); sampling of water/chemistry, particles, biology and sediment; and a need for ensembles of measurements (e.g. all or most physical, chemical and biological variables and rates used in earth system models). When prioritization was pushed the resulting ranked list closely resembled those from the EOV (GOOS) framework, with the addition of a need for intervention, sampling and ensemble measurements.

For biogeochemical sensor priorities (in addition to process capability as above) clear themes emerged, with a need for additional sensor capabilities to better constrain the inorganic carbonate chemistry system, nutrients and to a lesser extent particles and trace metals suggested as priorities.

For biological sensor priorities, contributions were more varied reflecting the breath and diversity of biological marine sciences. Imagery, acoustic, and molecular sensors emerged as a trio of focal areas, with high potential over the next 5-10 years. Systems for phytoplankton primary production were assessed as being available in shorter timescales.

For both biogeochemical and biological applications, an investment in the development of samplers (water, particles, eDNA, sediment, biology) and their integration into low-carbon observing systems was seen as likely to accelerate scientific achievement.

This workshop acts as a foundational step in understanding the future measurement needs of the marine science community, to inform NERC's decision on how to upgrade the marine research infrastructure provided to the UK science community.

Engagement Summary

In late 2023, the Future Marine Research Infrastructure programme (FMRI) sponsored its second[1] community engagement exercise, this time focusing on the technological and scientific priorities for future ocean measurement systems. Jointly convened by the National Oceanography Centre and Defra, 25 experts were invited to a two-day workshop that brought together diverse perspectives to challenge established thinking. These outcomes were then shared at a virtual workshop with an additional 43 participants from across the UK and the world. Slido was used to capture feedback from the virtual workshop participants. There was the opportunity for all 139 individuals who registered an interest in this consultation to provide anonymized post-workshop responses via an online form, and this was combined with other written submissions in the synthesis.

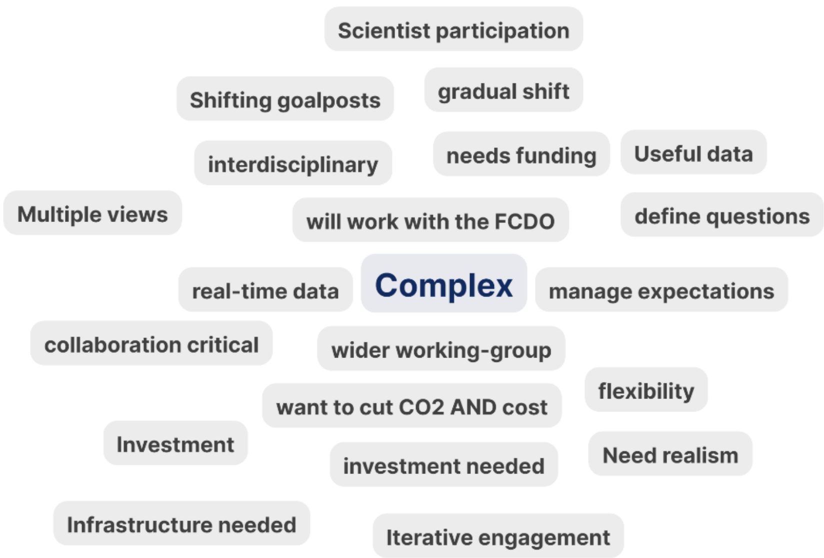

Figure 1. What are your key takeaways from the virtual workshop?

Figure 2. [Left] Plenary discussion at the in-person workshop; [Right] The workshop hosts: Rohan Allen and Matt Mowlem.

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[1] In 2022 FMRI convened an [Embedding Net-Zero Capabilities in Digitally Enabled Ocean Science] engagement exercise.

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