Net Zero Oceanographic Capability - Scoping Study

WP1: Future Science Need

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In 2019, UKRI (NERC) commissioned the National Oceanography Centre to identify the 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. 6 work packages were initiated to examine the science and policy drivers for a future research capability and the various technologies that could enable the capability. The findings of the 6 work packages and a number of independent reports commissioned under the NZOC banner were combined in the NZOC Summary Report that provides more information about the project.

This report covers the detailed findings of Work Package 1: Future Science Need.

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Executive Summary

UK marine science spans a wide range of multi- and interdisciplinary topics, including fundamental drivers of ocean circulation, understanding ecosystem behaviour and its response to climate change, causes of and implications of polar ice cap decline, and implications of ocean warming on sea level, weather and climate. Marine science includes investigating problems of societal relevance such as food security, the geohazards of sea level rise, storm surges and underwater volcanoes, and understanding the consequences of offshore development on the ocean's health while realising the economic and carbon benefits of a sustainable blue economy. Furthermore, marine science is intrinsically linked to Net Zero carbon objectives since the oceans are major sinks of anthropogenic carbon and the excess heat caused by anthropogenic greenhouse gases[1].

The UK has a strong record of world-leading oceanographic science, with UK researchers responsible for 10% of oceanographic and marine geosciences papers, and increasing international collaboration over the past 50 years (Mitchell, 2020). This longstanding legacy is reliant on marine research vessels and ship-based equipment as one of the most reliable and accurate means of carrying out marine science[2]. Ship-based observations allow the UK to address global challenges, to support ocean observing networks, make measurements not possible via satellite or Argo profiling floats, or in remote and extreme environments[3]. Sustained in situ observations, including from research vessels, need to be supported as "an infrastructure delivering Ocean data as a public good"[4]. Ships are used for full-depth comprehensive reference inventories of the ocean through repeat hydrography lines, calibration and validation of autonomous platforms, calibration and validation of satellites, to deploy and recover moorings and mobile assets, and to carry out large-scale, intensive process studies which generate impactful new understanding and are used to further iterate and evolve the strategies for sustained ocean observing. The observational methods currently in use have been developed and tested over decades and are the 'tried and true' methods used to investigate both ocean processes and climate change.

However, the recent expansion in marine autonomous systems (MAS) and Earth observation (EO) has further expanded the tools available to oceanographic research and opened up new avenues of research that were not previously available. Highlight examples include the global deployment of the Argo profiling float array, envisioned during the World Ocean Climate Experiment (WOCE) in the 1990s and fully-functioning since 2007 (Riser et al. 2016). These autonomous floats have provided near-real time global mapping of ocean temperature and salinity in the top 2000m, at roughly 3° spatial resolution and 3-month temporal resolution, and have infilled gaps in ocean observing (especially in the Southern Hemisphere) and underpinned dramatic improvements to weather and climate forecasting. The launch of the TOPEX/Poseidon altimeter in 1992 provided ~weekly maps of sea level anomaly across the globe (66°S to 66°N) showing the pervasiveness of ocean mesoscale

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[1] An open letter by Peter Thomson, UN Special Envoy for the Ocean, to Patricia Espinosa, Executive Secretary of the UNFCCC, https://ocean.economist.com/governance/articles/cop26-and-the-ocean-climate-nexus, [*accessed July 2021*]

[2] Nieuwejaar, P., et al. (2019) Next Generation European Research Vessels: Current Status and Foreseeable Evolution. Heymans, JJ., Kellett, P., Viegas, C., Alexander, B., Coopman, J., Muñiz Piniella, Á. [Eds.] Position Paper 25 of the European Marine Board, Ostend, Belgium. 140pp. ISBN: 978-94-92043-79-5 DOI: 10.5281/zenodo.3477893 [*Accessed September 2020*] and European Marine Board Policy Brief 7, https://www.marineboard.eu/publication/EMB-publications [*Accessed July 2021*]

[3] Tropical Pacific Observing System (TPOS) 1st Report, https://tpos2020.org/project-reports/ [*Accessed July 2021*]

[4] European Marine Board Policy Brief 9, https://www.marineboard.eu/publications/sustaining-situ-ocean-observations-age-digital-ocean [*Accessed July 2021*]

eddies (small ‘whirlpools’ of water ~100km across with rotational speeds of 1kt). The launch of this satellite has been likened to the repairs to the Hubble telescope—where once our vision of the ocean surface was blurry, we could now see the extent of smaller-scale circulation patterns in the ocean (Chelton et al. 2007). The Autosub mission under the Antarctic ice shelf, Pine Island Glacier, in 2009 provided first-of-its-kind measurements of ocean temperature and salinity providing new insights into the rapid warming and potential tipping point of the West Antarctic Ice Shelf (WAIS) collapse (Jenkins et al. 2010). These examples of where MAS and EO have provided a step-change in capability are based in physical oceanography, which is one of the more mature subfields in marine research, but we can anticipate that further step changes will be possible with the expansion of MAS and sensing capabilities in biogeochemistry.

At the outset of a transition towards Net Zero, there is critical need for a method to *evaluate carbon cost against information value*. Autonomous platforms, housing arrays of sensors, provide one key means of delivering science capability at low financial and carbon cost, as well as providing important opportunities for observing challenging environments (such as the polar regions and the deep ocean) and making high temporal and spatial resolution measurements. In contrast, operating global-class research vessels attracts a high cost (financially and carbon). However, the data returned are also of highest accuracy, being calibrated using laboratory analyses and international reference materials, and enable many variables to be measured in the same time and place, enabling maximum value to be extracted from datastreams collected from more autonomous systems. In these cases, the information value may be very high, compared to alternative lower carbon approaches, and an integrated multiplatform approach recognising the linchpin role of research vessels is likely to deliver optimum information value. Without a thorough and accurate assessment, a move to using new, lower carbon approaches could be a false economy, leaving the UK marine science community in a compromised position: unable to carry out world-leading science, unable to contribute to global ocean observing, and unable to assess the value of the ocean carbon sink in its territorial and international waters.

Through the Baseline Review, we showed that an ever increasing number of UK marine scientists are using autonomous technology and low carbon options. However, we also identified a number of use cases and case studies where UK marine science is unlikely to be achievable through Net Zero approaches within 15 years (e.g., deep rock drilling, marine ecosystem studies with measurements of rates of production and respiration, measurements of isotope systems within marine settings), and in other cases where the relative information value to the carbon cost might indicate that the carbon is well-spent (e.g., measurement of large-scale ocean circulation through boundary mooring arrays, or complex multi-disciplinary process studies necessary to underpin development of Earth System models). Eventually, and with substantial investment, these activities may be achievable through Net Zero approaches, but whether the assessment is sound (the anticipated carbon reduction against development cost and anticipated information value) is unclear.

Environmental and climate scientists overwhelmingly and urgently support a move towards Net Zero and zero emissions globally. **However, within NERC and the UK marine science community, we cannot overstate the importance of getting the transition to Net Zero right.** Any transition to using new methods must be a flexible but managed process, requiring overlap between old and new methods, due consideration to accessibility, and subjection of the verification and validation steps to review by the broader science community. Without due diligence, the transition could render long time series invalid or increase uncertainties in the output beyond the point where e.g., anthropogenic change can be assessed, resulting in new data collection efforts having reduced value[5]. If a move to Net Zero necessitates that we 'leave behind' certain disciplines, there must be a strategic vision and objective basis (e.g., information value vs carbon cost) upon which to make that decision. Furthermore, we must not lose sight of the importance of curiosity-driven discovery science and informed exploration.

Keeping these issues in mind, and towards the aim of getting to Net Zero, we have identified both a set of recommendations that take advantage of the opportunities of emerging technologies, but also a set of 'critical risks' which, if not adequately guarded against, will leave the future UK oceanographic capability unable to fully participate in world-class science or otherwise reliant on external providers of oceanographic capability. We further note that many of the recommendations are *necessary, but not sufficient* to guarantee that the Net Zero Oceanographic Capability will not represent a substantial reduction in capability. The UK marine science community, rather than the technologists and engineers, stands to lose if a substantial reduction is not avoided.

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[5] Tropical Pacific Observing System (TPOS) 1st Report, https://tpos2020.org/project-reports/ [*Accessed July 2021*]

Summary of recommendations

At present, the UK is home to a thriving and robust community of observational marine scientists. The current oceanographic capability is one of the best in the world. Given the strong imperative to move towards Net Zero, while retaining world-class oceanographic capability, the transition must be

- strategic – *what process will be used to priorities discipline-specific developments?*
- optimised - *where will developments in the observing approach lead to the biggest carbon savings?*
- planned – *is the marine science community ready to take advantage of new approaches?*
- measured - *are we on track with developments that will enable us to meet science goals?*
- flexible – *how will the transition account for slowdowns or roadblocks to progress? where can we make better use of global oceanographic capability?*
- opportunistic – *what new opportunities, disciplines, science questions can we address with the new capability that were previously out-of-reach? What new communities can now access observational marine science where present barriers have reduced access?*

We have identified 10 key recommendations towards ensuring that a transition to Net Zero is maximally effective and results in a minimal reduction to the UK's oceanographic capability. Specific actions and measures are associated with these recommendations are included in the Roadmap section. We note again that satisfying these recommendations is *necessary but not sufficient* to guarantee a successful transition to Net Zero, and that when undertaking an effort of this scale and on such a short timeline, many development activities must succeed in parallel to avoid a substantial reduction in UK oceanographic capability.

Highest priority recommendations

These top recommendations focus on strategic direction, ensuring developments are fit for scientific end-users, that the transition to Net Zero can mark milestones and evaluate progress across a range of parallel and interlinked requirements, and that scientists are primed to use the new approaches afforded by a Net Zero approach.

1. **Strategic oversight.** Evaluate (repeatedly) the priority development areas, accounting for strategic decisions and optimal approaches to reduce carbon.
2. **Co-design between technologists and scientists.** Ensure scientists are embedded within or leading technology development efforts, rather than passive recipients of newly developed technology. This one step will mitigate against several of the critical risks identified below, yet is not common practice in the current funding landscape. Both observational scientists and modellers should be involved in order to extract optimum value from data.
3. **Milestones to measure progress.** The development process is not linear and the complexity of marine fieldwork to trial methods adds uncertainty. A set of milestones must be developed (e.g., 'proven sensor accuracy' or 'pilot study results accepted by the international community') to evaluate whether progress towards Net Zero is on track, and if not then the transition timing and its feasibility must be re-evaluated.
4. **Workforce training.** Ensure that marine scientists can capitalise on new data approaches and the data ecosystem (see Work Package 6). Invest now in skills training for existing and future marine scientists to ensure there are sufficient trained specialists to capitalise on new data approaches.

Recommendations to capitalise on opportunities

Additional recommendations are based on the new opportunities which should not be neglected on as we move towards Net Zero:

5. **Invest in an equitable, diverse and inclusive marine science community.** The Net Zero approaches (e.g., moving towards wider use of autonomous platforms) may reduce barriers to access for the field of observational marine science. To capitalise on this opportunity, establish a practice of monitoring ED&I on the path to Net Zero, to evaluate expected and unforeseen consequences of new technology developments.
6. **Work with industry and other private sector partners** to take advantage of technology already under development and open up new opportunities.
7. **Engage with international stakeholders** to identify UK contributions to global observing and evolve priorities to capitalise on Net Zero approaches.

Immediate recommendations

Additionally, there are activities that can be carried out now to reduce carbon while minimally impacting oceanographic capability.

8. **Optimise ship use** to encourage collaborative efforts and a systems/fleet approach over the next decade to reduce the carbon impact for activities where ships are required.
9. **Increase available bandwidth on existing ships** to capitalise on remote participation in ship-based activities where possible.
10. **Develop a flexible hybrid system of "autonomy where possible"**, identifying ship-based activities that can be replaced or reduced through only moderate changes in current autonomous approaches.

Critical Risks

The recommendations outlined above, and in greater detail in the Roadmap section, are designed to mitigate against critical risks to the success of a Net Zero transition. The risks identified below represent significant risks that in spite of significant investment, the Net Zero solution may still not fulfil the needs of the UK marine science community, and should be considered when planning a transition strategy. The risks are that:

1. **Only a subset of current marine science observations is likely to be achievable in the near term without a global-class, multi-purpose research vessel.**
   If the Net Zero Oceanographic Capability does not meet all current observing requirements, then the UK marine science community will shift focus to those scientific questions that are achievable or otherwise rely on external providers.
2. **Net Zero infrastructure is not fit for 'experimental observation', limiting UK marine science to making routine observations** Marine observations can be broadly cast into two separate but interlinked purposes: 'sustained observations' and 'experimental observations'. Sustained observations include activities such as repeat hydrographic sections, where

routine measurements are made to monitor on an ongoing basis and contributed to a global dataset for large-scale analyses, and to provide context for experimental observations. Experimental observations are typically taken for a limited observing period for research and development purposes to advance human knowledge and to inform, evolve and innovate the sustained observing system. In many cases, these experimental observations are bespoke, first-of-their-kind and not necessarily repeated.
If development of the Net Zero infrastructure focuses on replacing routine observing methods, then UK capacity to carry out the more complex, experimental observations will be reduced.

3. **Sensors developed for observing on autonomous platforms fail to meet observing requirements, rendering Net Zero infrastructure unfit for 'sustained observations' and limiting the scope of scientific questions that can be addressed.** The current approach to oceanographic observing relies on trained laboratory scientists carefully taking water samples which can then be analysed in on-board laboratories or preserved for later analysis in land-based laboratories. This approach enables highly precise and accurate measurements which are required in many situations to measure low concentrations or to resolve small signals of change, including for sustained observations of 'climate quality' data.
   If sensors do not meet observing requirements and have e.g., reduced accuracy, reduced precision or irreducible drift, then the marine science community will be unable to use them for scientific questions where accuracy and precision are required.
4. **Inadequately demonstrated methods will be met with scepticism by the international scientific community, reducing the value of UK marine science outputs.**
   If methods are replaced before sufficient peer-reviewed evidence for their efficacy has been generated and trust built in them, then science outputs generated using these data will not be accepted by the international community, thus reducing the value and impact of UK marine science.

Achieving Net Zero is one of the most important societal goals over the next decades. NZOC is part of the solution. We can not only maintain but also build on the UK's world-class marine science capability – essential for meeting Net Zero targets – with equitable and fair strategic planning, co-design of new approaches, and by taking advantage of new opportunities that arise from the emerging technologies.

Introduction

Review Scope

Our oceans are crucial in regulating global climate and are essential to life on Earth. Multiple and cumulative stressors are impacting the marine environment, including pollution, acidification, extraction of natural resources, extreme weather and climate change. Scientific understanding of the current and projected marine systems, and their sensitivity to these stressors, is going to be essential in order to manage the oceans, and achieve sustainability goals at local, regional and global scales. However, these systems are complex, with a large number of interacting physical, chemical, biological and sociological components, and function over a wide range of temporal and spatial scales. New technologies and infrastructure are going to be increasingly important to address these challenges, together with multi-disciplinary and international approaches and co-production with stakeholders. With the start of the UN Decade of Ocean Science for Sustainable Development in 2021, and continuing tasks associated with achieving the UN Sustainable Development Goals (SDGs), there is a clear motivation not only for more research, but for sustainable science.

NZOC (Net Zero Oceanographic Capability) is a NERC scoping project informing planning for the future low carbon oceanographic research capability in line with UKRI's objectives of becoming a net zero organisation by 2040. The National Oceanography Centre's National Marine Facilities (NMF) division is leading a team of national experts investigating the drivers and enablers of future oceanographic research. Work Package One (WP1) aims to i) carry out a horizon scan of marine science activities in the UK, and ii) capture the multiple science drivers that will help to shape future research directions and infrastructure investment over the next 15 years, given NERC's primary objective of maintaining and enhancing the UK's world-leading position in the field of oceanographic research.

The aims of this report are to:

i) communicate the results of the Baseline Review and horizon scanning activities;
ii) summarise international strategies for ocean observing;
iii) highlight the key outcomes from the WP1 workshop "*The 21st Century Marine Scientist - Delivering science in a net zero world*", survey and interviews; and
iv) present a roadmap for future UK marine science to optimise science delivery in the context of UKRI's Net Zero goals.

Net Zero Definition

For the purposes of this report, we are assuming that 'carbon emissions' is an inclusive term to refer to all greenhouse gases (GHGs) known to have a negative impact upon climate change. We are using the UKRI[6] requirements for 'Net Zero': "Reducing and mitigating all carbon emissions from our owned operations, including our measurable scope 3 emissions [*value chain emissions, see Table*], in line with the IPCC recommendations and the UK government commitment. We will strive to achieve 'net-zero' sooner than 2040, but we do not yet have all the solutions we need to achieve this."

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[6] UKRI Environmental Sustainability Strategy (https://www.ukri.org/about-us/policies-standards-and-data/environmental-sustainability/) [*Accessed April 2021*]

Scope 1	Scope 2	Scope 3
• Fuel combustion • Company vehicles • Fugitive emissions	Purchased electricity, heat and steam	• Purchased goods and services • Business travel • Employee commuting • Waste disposal • Use of sold products • Transportation and distribution (up- and downstream) • Investments • Leased assets and franchises

Table 1: GHG emissions are categorised into three scopes by the Greenhouse Gas Protocol, a commonly-used international accounting tool (source: The Carbon Trust[7]).

Science drivers

Background and motivation

Science drivers for NERC marine science include discovery science, to understand how the Earth works, and strategic science, to address key societal challenges. To date, observational marine science has a long history of relying on traditional ship-based measurements, and through the exceptional capability provided by the fleet of global-class research vessels. Achievements have included measuring microplastics in the ocean, quantifying the time-varying large-scale ocean circulation, measuring oceanic heat delivery to Antarctica's vulnerable ice shelves, and contributing to international programmes to monitor the climate (Argo float program, GO-SHIP hydrographic sections) and assess the climate (IPCC).

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 WP1 workshop (see Appendix) identified emerging questions in order to form the basis for discussions of the technological development that would be needed to address them, either in the

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[7] Carbon Trust (https://www.carbontrust.com/resources/briefing-what-are-scope-3-emissions) [*Accessed April 2021*]

absence of large multi-disciplinary research ships or by capitalising on new capabilities provided by marine autonomy, sensors and improved data management.

Observational marine science span a wide range of parameters within sub-fields of biological, physical, chemical and geological marine science; sampling requirements span a large dynamic range in space and time. Some applications require very rapid sampling over a short duration (e.g., storms, extremes, seismicity, small-scale processes), while others require decadal timescale measurements spanning ocean basins (e.g., anthropogenic change). Some measurements are made near the surface where waves, marine traffic and fishing activity present risks, while others are in the ocean abyss which presents challenges for pressure and positioning. Additionally, as the ocean is continually changing (the parameter C may vary in x, y, z and t), the speed at which the platform moves (very fast for satellites, 10 kts for ships, somewhat slower for the current suite of MAS) can limit the utility of observations. **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.** Sustained observations, including for climate monitoring, require long time series, which present challenges in data accuracy and cross-calibration between established and new methods to ensure continuity of the data sets. Process-based or experimental studies include rate measurements (e.g., nutrient fluxes, biological production, particle sinking rates and remineralisation), and require accurate measurement under controlled conditions of parameters that cannot be currently be achieved using sensors (e.g., respiration, degradation, carbonate chemistry, tracers etc.). Sustained observations provide key baseline information for experimental studies; the latter enhance our understanding of oceanic processes that feedback into our systems design for the former.

Whilst there is a clear commitment within the UK marine science community to minimise – or even eliminate – carbon emissions, there is also strong motivation to maintain the world-class capability for sustained and experimental observations that underpin our mechanistic understanding of the oceans, forecasts and predictions. **There was recognition in the WP1 workshop that there is a need to move from broad correlations to understanding connections, processes, and mechanisms in order to have greater predictive power and confidence.** There is a need to engage with emerging technologies that can help in reducing the main carbon costs of marine research (i.e., fuel consumption by large research vessels). However, there is also a need to evaluate the carbon cost against the value of the information obtained: observations that are critical to climate studies are also essential for achieving Net Zero.

Present technology enables the wide range of parameters to be measured using sensor and laboratory-based techniques from NERC's multi-purpose global class research vessels. The required space-time scales of observations are achieved through a range of technologies including satellite, sensors on moorings and anchored to the seabed, decadal repeat hydrographic sections, and shorter duration, potentially higher resolution targeted sampling efforts. While some of the science drivers include long-term monitoring, and cruise tracks and sampling are predetermined (e.g., GO-SHIP hydrographic sections), other expeditions are more experimental. In these cases, new techniques may be developed using onboard laboratories; specific features of interest identified by close, real-time interaction between onboard scientists and the data collected, enabling responsive, targeted sampling; cross-disciplinary advances are enabled by the close living and working conditions for scientists onboard research vessels. There is the potential for some of this close interaction to be replicated through a virtual lab, but it is a capability that has not yet been trialled at significant scale.

Ocean observing: Sustained and experimental

Ocean observing endeavours fall into two broad, but interlinked categories and can be used to guide thinking about marine observing. The preferred nomenclature was identified in the OceanObs'19 paper on GOOS (Moltmann et al., 2019):

- **Sustained observations**: measurements taken routinely that are committed to monitoring on an ongoing basis. These measurements can be for public services or for Earth-system research in the public interest. They also provide context for experimental observations.
- **Experimental observations:** measurements (taken for a limited observing period) that are committed to monitoring for research and development purposes. These measurements serve to advance human knowledge, explore technical innovation, improve services, and in many cases, may be first-of-their-kind. These types of intensive process studies are also used to further iterate and evolve the strategies for sustained ocean observing

Typical applications for sustained observations include for climate, forecast and hazard warnings or ocean health applications. They may also be referred to as 'marine monitoring' which can mean that the data collection is at the request of a statutory agency for a specific purpose, e.g., to aid in management. Efforts for climate monitoring in particular may require high data accuracy to identification very small trends (e.g., salinity trends of 0.001 psu/decade for abyssal ocean warming (Purkey et al., 2019) and broad spatial coverage (typically global) which may be at coarser spatial resolution. Many of the international strategy initiatives outlined in the preceding sections refer to sustained observations.

Experimental observations or 'process studies' are used to elucidate specific processes that occur in the natural environment, and are typically time-limited and regionally specific. They may require higher spatial- and/or temporal-resolution, and may have lower requirements for data accuracy. In this way, sustained observations can be thought of as used for 'ocean climate' while experimental observations are for 'ocean weather.

While the two types of observations are interlinked and, at present, use much of the same observing technology, they are not interchangeable. The Argo profiling float array, for example, is designed to measure the state of the ocean at an approximate resolution of 3° and 3-months, which would not permit the investigation of e.g., oceanographic processes at the meso- or sub-mesoscales (~100km or ~5km). Both types of observations currently rely heavily on research vessels: sustained observations, for the highest quality data that enables climate-type questions to be addressed, and experimental observations, for high resolution in space and time to capture fast-evolving processes. Both sustained observations and experimental process studies can require in situ measurements, and/or the collection of a physical sample for later analysis, and both will require the recording of meta-data.

The technological development for sustained observations (as outlined in the strategy documents above, and including GO-SHIP, Argo global profiling float program (Roemmich et al., 2019), AMOC observations (Frajka-Williams et al., 2019), CO2 measurements (Wanninkhof et al., 2019), polar oceanography (Meredith et al., 2019), Earth's energy imbalance (Palmer et al., 2019), ocean drilling) will not necessarily be fit-for-purpose for 'process-type' discovery science. *However, there is an interdependence of sustained and experimental observations: process studies and pilot projects are essential for informing, evolving and innovating the sustained observing system.*

UK National Marine Facility usage over the last five years

The UK is involved in both sustained and experimental ocean observing. To assess the temporal trends and future science needs, we conducted a baseline review of National Marine Facility usage over the last five years to assess the disciplines represented by the cruise, the equipment used, and the geographic region.

Summary of methods

The overall aim was to produce a status report of recent UK marine science ship and equipment.

- Cruise reports were collated for the three UK global-class research vessels (RRS Discovery III and IV, RRS James Cook, and RRS James Clark Ross) for two time periods, 2005-2010 and 2015-2020. These reports were accessed from the BODC open repository, and were surveyed for the main subject discipline and geographic location.
- Roughly 10% of cruise reports were selected at random between 2015-2020 (10 of 100) for a more detailed assessment including cruise length and user-supplied equipment.
- Reports from the Cruise Programme Review Group (CPRG), 2017-2020, were assessed for cruise disciplines (physical oceanography, chemical oceanography, biology/fisheries, geology/geophysics, and meteorology), as indicated by the Principal Science Officer (PSO).
- Reports on Ship-time & Marine Equipment (SME) and Autonomous Deployment Forms (ADF), 2017-2020, were assessed for NMF pool equipment requests and usage.
- The impact of cruises was assessed for the last five years through a publication search using Google Scholar (search term example: “RRS Discovery DY081”) and examination of citations using long-term datasets from the following projects: Porcupine Abyssal Plain (PAP), Atlantic Meridional Transect (AMT), and Rapid Climate Change (RAPID 26°N array).
- An online survey sent to UK marine scientists was carried out in January-February 2021 to assess current and projected use of autonomous technology, with a total of 44 respondents.
- The results of these manual searches were compared to the automated keyword search app developed by Liam Brannigan (2021).

Cruise disciplines

Our findings illustrate that there has been no major change in the principal discipline of expeditions on NERC/BAS ships from 2005-2010 and 2015-2020 (Fig. 1-2), but that the NERC/BAS ships serve a wide range of subjects/disciplines (Fig. 3, Box 1). In addition, there is a strong representation of multidisciplinary research cruises in recent years, as identified by the Principal Science Officer (PSO). Out of the 37 cruises (*Cook* and *Discovery*) identified since 2017 where cruise discipline was reported by the PSO, 25 cruises (68%) were classified as relating to two or more disciplines, and 16 (43%) were classified as relating to three or more disciplines (Fig. 3). The UK’s strength in multidisciplinary research has been featured in European Marine Board reports on future research vessels (Box 1).

Cruise equipment

There is a wide range in both NMEP and user-supplied equipment required for scientific research cruises (Table 2, Fig. 5-7). Research is carried out using both “tried-and-tested” equipment (e.g., CTD rosettes) and more novel autonomous technology, the latter being used heavily during the COVID-19 pandemic “recovery” phase when the NERC ships were in port. Out of the 44 survey respondents across the marine research sector, 34 currently use autonomous technology in their work (77%) (Fig. 8). At present, there is substantial interest and uptake of using ocean gliders for marine research.

From the NZOC literature analysis (Brannigan, 2021[8]) the UK has adapted to using autonomous vehicles much more rapidly than the global average. Over the last 5 years, the UK has been publishing results based on gliders at 2-3 times the rate of the global average. Additionally, the UK marine science fields have a broad geographical range from the Arctic to Southern Ocean, though in the Atlantic tends to focus on tropical and temperate latitudes. With recent investments by NERC, e.g., Oceanids[9] and the NEXUSS CDT, it is likely that this uptake of autonomous platforms will continue to increase.

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

[9] https://noc.ac.uk/projects/oceanids [*Accessed May 2021*]

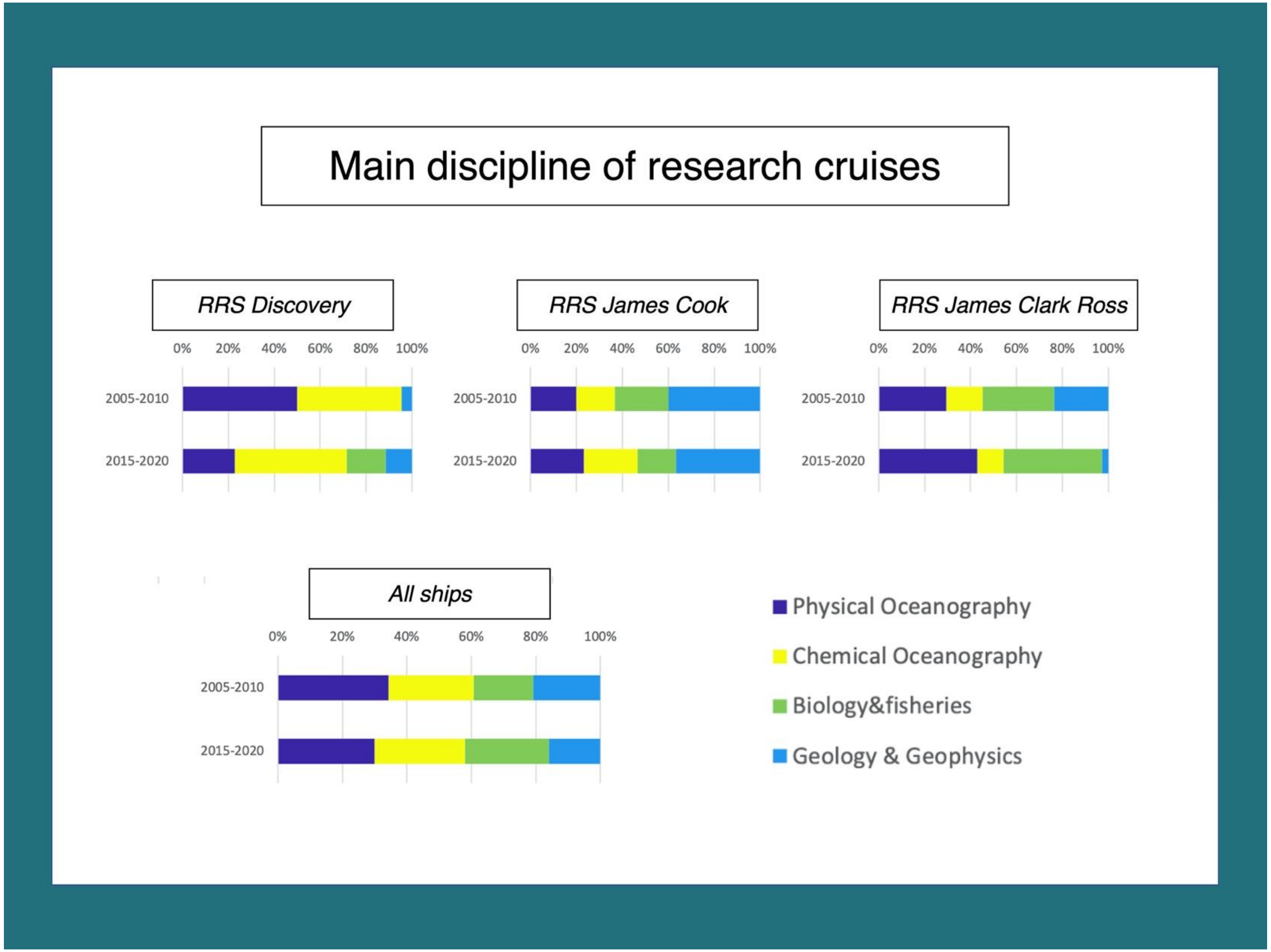


Figure 1: The main research discipline, assessed from cruise reports, for each of the main UK research vessels from a period of 2005-2010 and 2015-2020. *Note for the *RRS Discovery* that this summary includes both *Discovery* ships III and IV.

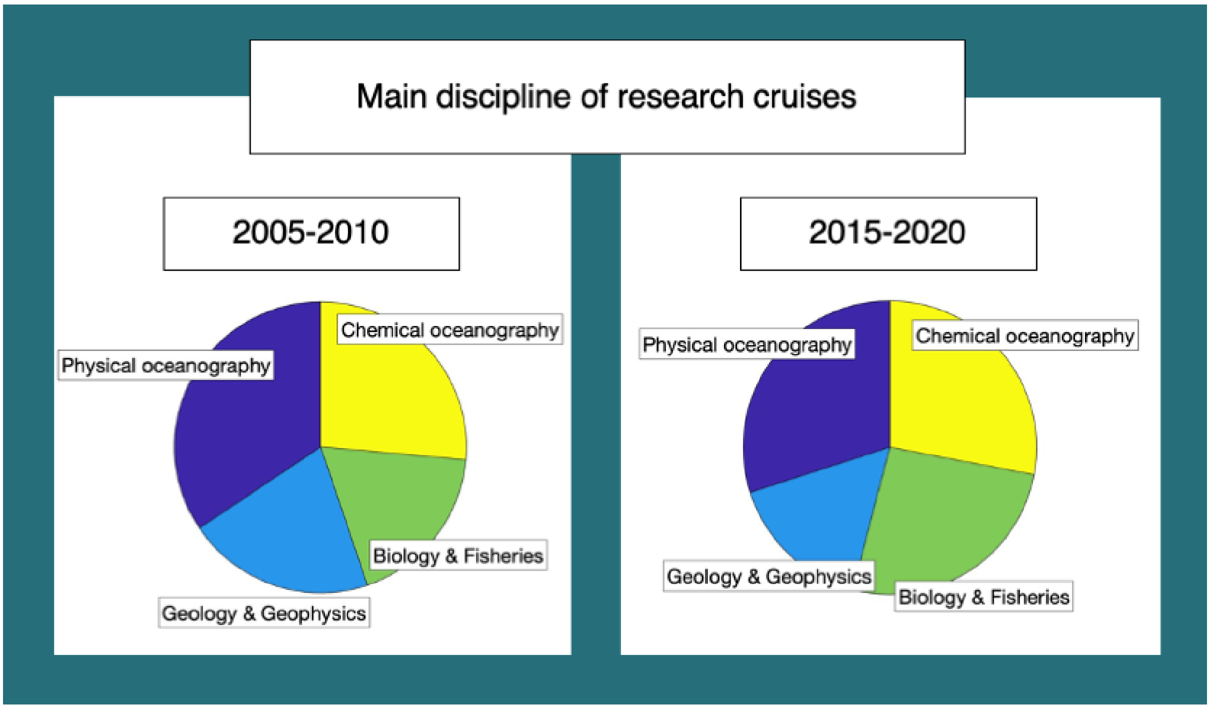
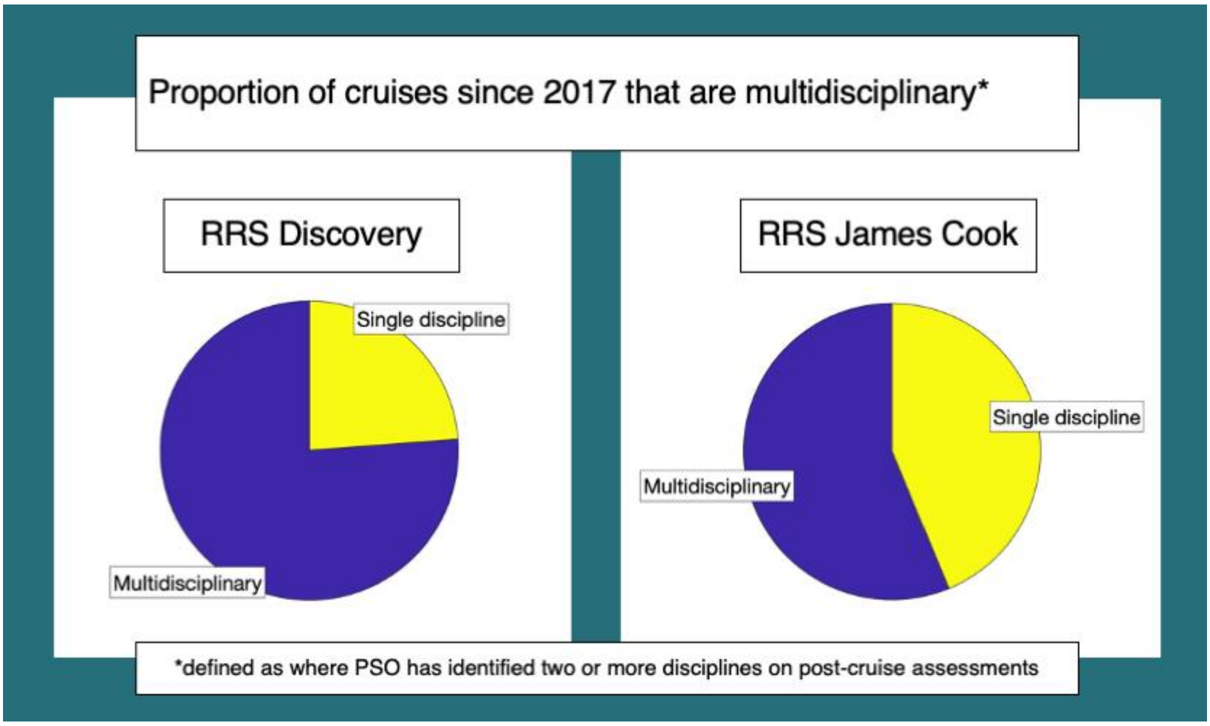


Figure 2 (Above): The main research discipline, assessed from cruise reports, for all main UK research vessels as a whole from a period of 2005-2010 (left) and 2015-2020 (right). Note that both the *RRS Discovery* III and IV have been included.

Figure 3 (Below): Proportion of research cruises since 2017 that are identified as multidisciplinary according to CPRG reports.



Box 1: Case Study RRS Discover cruise DY081 - Isotope CYcling in the LABrador Sea ICY-LAB (ERC grant 678371)

The high-latitude regions are experiencing some of the most rapid changes observed in recent decades. Arctic temperatures are rising twice as fast as the global mean, Greenland's glaciers are experiencing significant mass loss, multi-year Arctic sea-ice is declining, and the Nordic Seas are warming at an accelerated rate.

Concurrently to the recently observed changes in ice dynamics and accessibility, there has been a significant increase in commercial interest of the natural resources in the ecosystems of the Arctic, surrounding seas and high-latitude North Atlantic. An understanding how natural resources – including fisheries, bird and mammal stocks that are essential for food and tourism – will respond in the future to increasing anthropogenic stress on a regional and global scale relies on an understanding of marine biogeochemistry and the sources and sinks of essential nutrients.

The overall aim of ICY-LAB is to understand nutrient and isotope cycling in the climatically critical but understudied regions of the Labrador Sea and Greenland fjords, and the impact of cryosphere, biosphere and hydrosphere on the biogeochemistry of the region and the global oceans. The approach of ICY-LAB was to capture the whole biogeochemical system in areas of marked environmental change using careful field sampling strategies, with research expeditions to coastal Greenland and the open ocean Labrador Sea. DY081 represented the key oceanic component of this sampling campaign, focusing on the influence of meltwater on nutrient cycling and biology today and in the past (Hendry et al., 2019).

To address the research aims, a multidisciplinary approach was taken, utilising both NMEP and user-supplied equipment including: the 6000m ROV *Isis*; a 6000m depth-rated video guided sampling system; autonomous sea gliders; fully instrumented Conductivity, Temperature, and Depth (CTD) sampling systems; a range of seabed coring systems; trace metal sea water sampling systems; specialist laboratory containers and sample storage containers; Stand Alone Pumps (SAPs); Ultra-short Baseline (USBL) acoustic positioning system; Acoustic Current Doppler Profiler (ADCP); Sub-Bottom Profiler (SBP); multibeam and single-beam echo sounders; onboard laboratories incorporating fume hoods and laminar flow cabinets; ultrapure scientific water production system; and -80°C freezers. The equipment was deployed using an extensive winch and cable system, and the *RRS Discovery*'s over-the-side handling systems and cranes. As noted in the Next Generation European Research Vessels report[10] "This equipment required installation and stowage space, and knowledgeable marine technicians to maintain and operate the equipment, all demonstrating the complexity of this category of research cruises and the multiple demands placed on deep-sea research vessels".

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[10] Nieuwejaar, P., et al. (2019) Next Generation European Research Vessels: Current Status and Foreseeable Evolution. Heymans, JJ., Kellett, P., Viegas, C., Alexander, B., Coopman, J., Muñiz Piniella, Á. [Eds.] Position Paper 25 of the European Marine Board, Ostend, Belgium. 140pp. ISBN: 978-94-92043-79-5 DOI: 10.5281/zenodo.3477893 [*Accessed September 2020*]

Cruise locations

A search of the cruise reports from 2005-2010 and 2015-2020 reveal that there has been little change in the main geographical focus of cruises, with the majority of cruises on the RRS Discovery and RRS James Cook being in the North Atlantic, and the RRS James Clark Ross most often visiting the South Atlantic/Southern Ocean (note that the JCR also plays a role in resupplying Antarctic research stations).

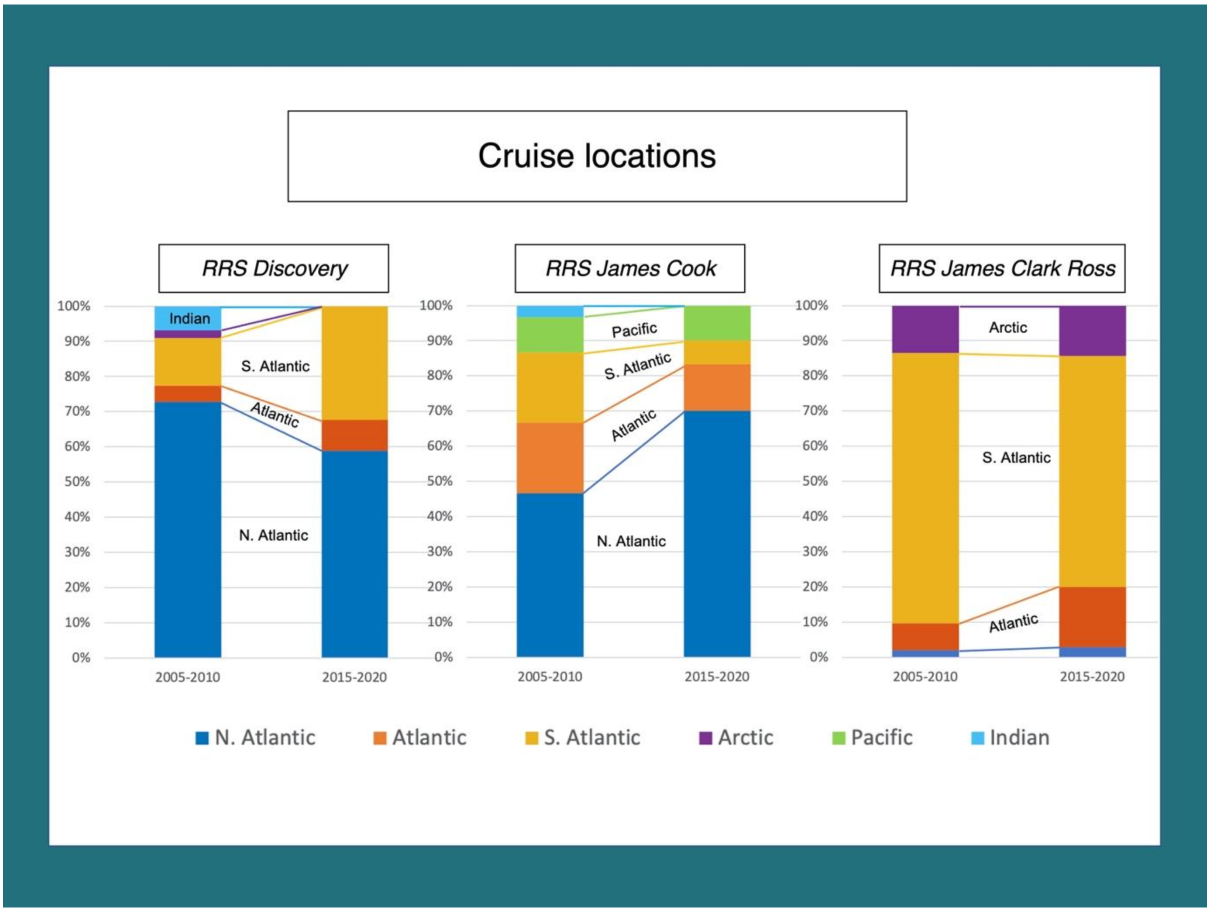


Figure 4: Geographical locations of cruises, assessed from cruise reports, for all main UK research vessels as a whole from a period of 2005-2010 and 2015-2020. Note that both the *RRS Discovery* III and IV have been included under “*RRS Discovery*”.

Equipment usage from cruise reports

Equipment usage on recent UK ships (based on a survey of 10 cruise reports) spans a wide range of both NMF-supplied equipment and user-supplied equipment. From the ship, standard tools such as a CTD rosette and vessel-mounted underway equipment were used, as were laboratories and freezers. Users additionally supplied a wide range of equipment comprising nets and tows, moorings, non-NMF autonomous vehicles, floats and buoys, in addition to a broad range of laboratory techniques to measure particular parameters from the ocean.

NMF supplied equipment	User-supplied equipment
On deck/deployed: • CTDs (stainless and titanium) and *LADCPs • Moorings and moored instrumentation • Gliders (including 2 x Microstructure gliders; one with nitrate sensor and one long endurance) • Stand Alone Pumps (SAPs) • Coring: Megacores, box cores (small and large – BAS and NMF owned) Vessel-mounted: • Vessel-mounted *ADCPs • Underway sampling (**CTD/F/Trans/pCO_2 and meteorology) • Underway geophysical data (***PES, EM, SBP, gravimeter) In lab: • Fume hoods • Clean lab/containers • Freezers (-20 and -80°C)	On deck/deployed: • Marine snow catchers • Zooplankton haul nets • Bongo nets/plankton nets • Plankton pump • Neuston net • Avani/Mid water/Agassiz trawls • Near-surface gas profiling buoy • Buoys (dust-collecting) • Moorings (including Wirewalker moorings, acoustic listening moorings) • Trace metal towfish • Underwater camera deployments • Broad-band ocean bottom seismometers • Non-NMF autonomous vehicles • SOCCOM/Deep ****ARVOR floats • APEX/RAFOS/Argo floats • Aerosol sampling In lab: • Nutrient autoanalyzer • Dissolved Inorganic Carbon (DIC) analyser/ DIC and Total Alkalinity titrators • Flow cytometry • Flame ionisation detection-gas chromatography and electron capture detection-gas chromatography • Oxygen optodes for respiration rates; Winkler titration • FastAct Fluorometer/Membrane inlet mass spectrometry • Chloro-fluorocarbon (CFC) analysis • High Precision Liquid Chromatography (HPLC) for pigment analysis • Microscopes

Table 2 (over the page): Equipment usage according to survey of 10% of cruise reports from 2015-2020. The average (mean) length of cruises in survey was 29 days (standard deviation 9 days); shortest 16 days, longest 46 (split over two legs). * (L)ADCP = (Lowered) Acoustic Doppler Current Profiler; ** CTD = conductivity, temperature depth rosette; ***PES = parametric echo sounding, EM = electromagnetics, SBP = sub-bottom profiler; ****ARVOR, APEX and RAFOS are types of profiling float.

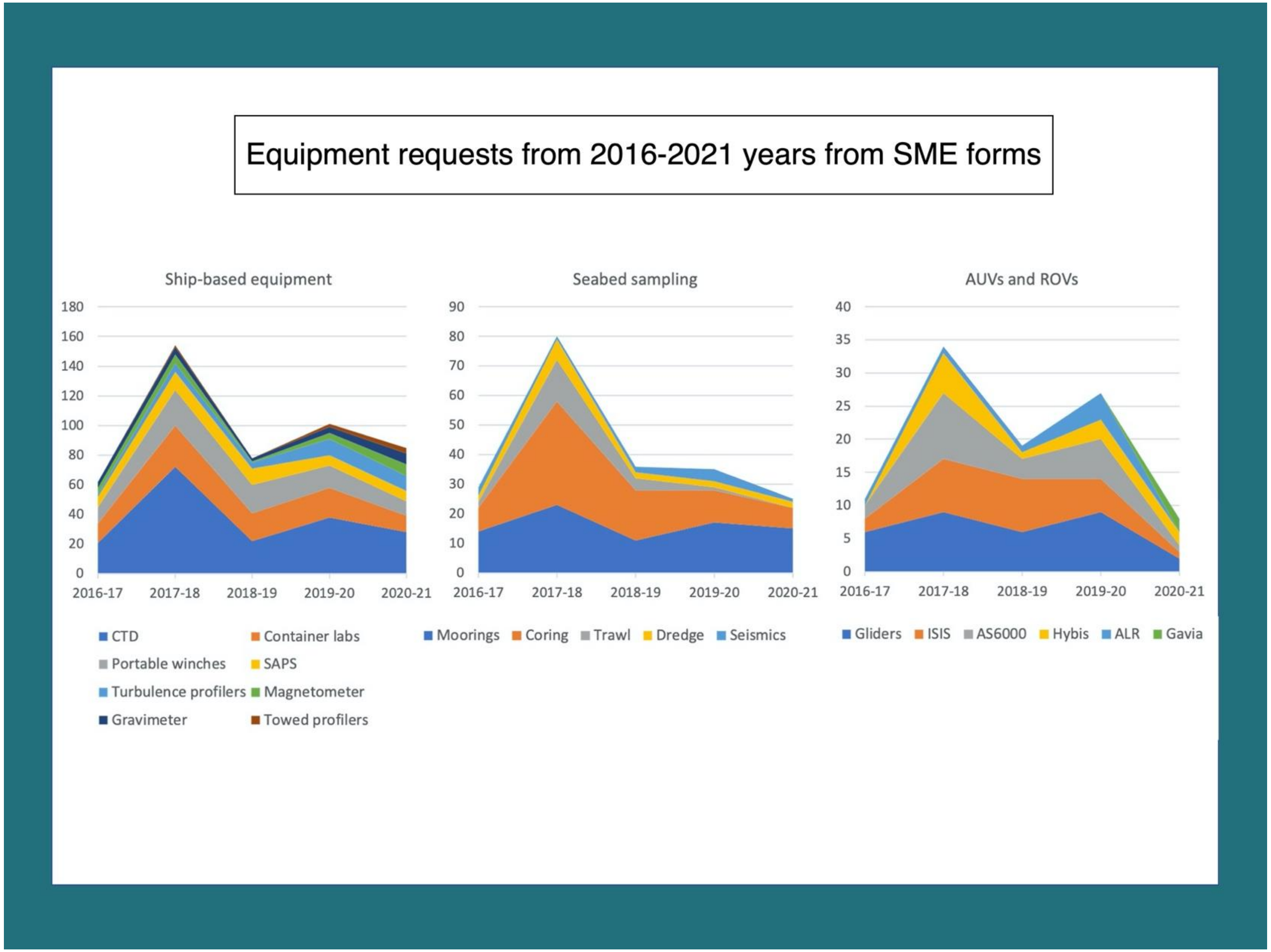
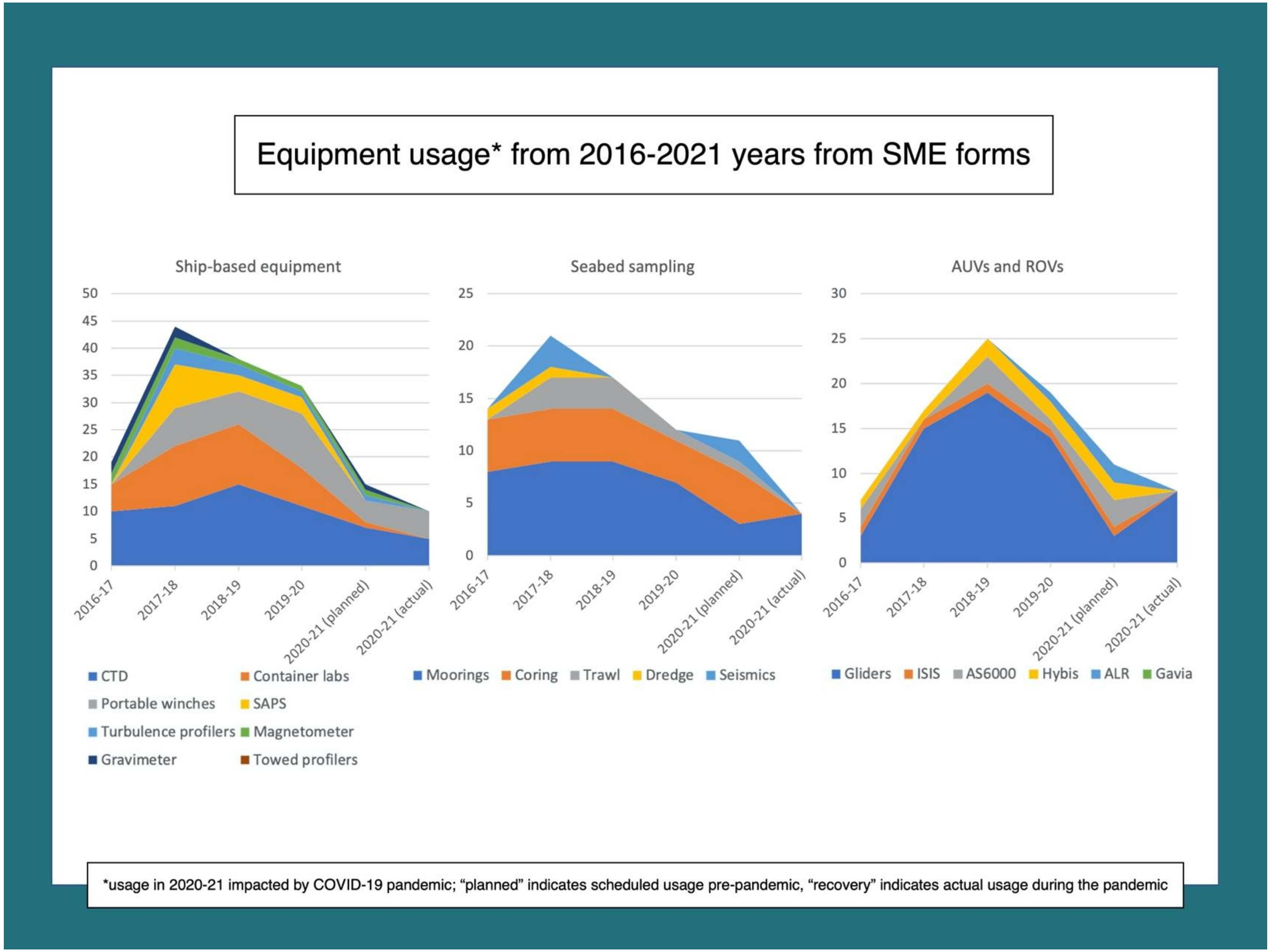


Figure 5: Equipment requests for research proposals according to SME and ADF forms since 2016-17. ALR = Autosub Long Range. AS = Autosub. ISIS = remotely operated vehicle (ROV) *Isis*.



Equipment usage* from 2016-2021 years from SME forms

*usage in 2020-21 impacted by COVID-19 pandemic; "planned" indicates scheduled usage pre-pandemic, "recovery" indicates actual usage during the pandemic

Figure 6: NMF Equipment Pool usage since 2016-17. ALR = Autosub Long Range. AS = Autosub. ISIS = remotely operated vehicle (ROV) *Isis*.

BODC keyword search: Cruise locations and disciplines

The automated keyword search of cruise reports within BODC developed by Brannigan (2021) provides a useful comparison to the manual survey activities. The automated keyword search included reports from additional vessels (*Hudson, Oceanus, Poseidon* and from the Rothera Time Series), in addition to the *RRS James Cook, RRS Discovery* and *RRS James Clark Ross*). Despite the different approaches, and necessary assumptions made in the automated search, there is a good comparison between the automated and manual methods. For example, the automated search results in a very similar message regarding main cruise locations, with the main locations being the North and South Atlantic/Southern Ocean.

A key advantage of the automated search is that it allows for a more thorough assessment of changes through time, which can be used to project trends into the future. Assessment shows trends towards polar regions, generally more challenging environments. Also trends towards tracers, bio-physical observations, geology and seabed, marine pollution, plankton studies and the use of automated vehicles, and away from hydrography and turbulence studies. However, these trends are region specific, for example studies referring to plankton, bio-physical observations and tracers are on a decline in the North Atlantic (Fig. 7).

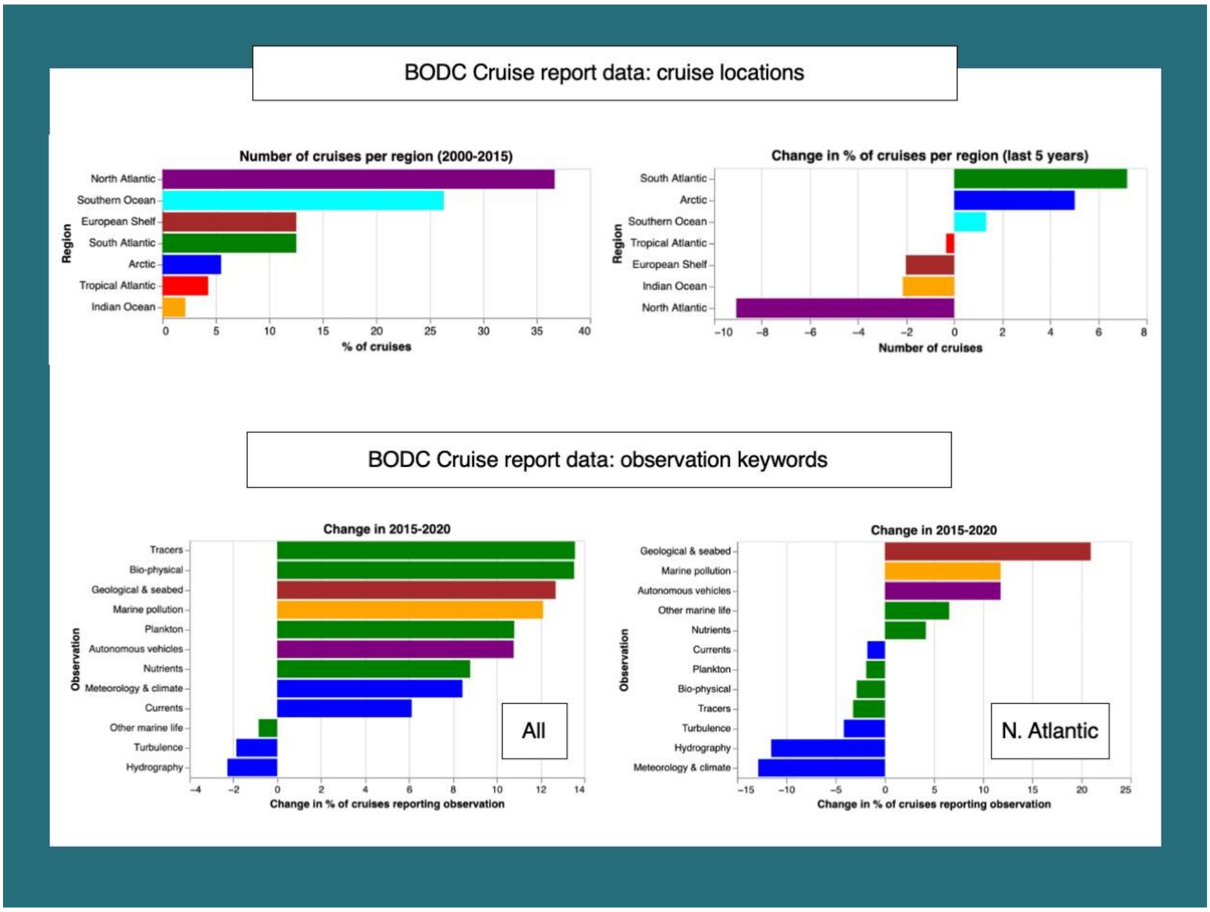
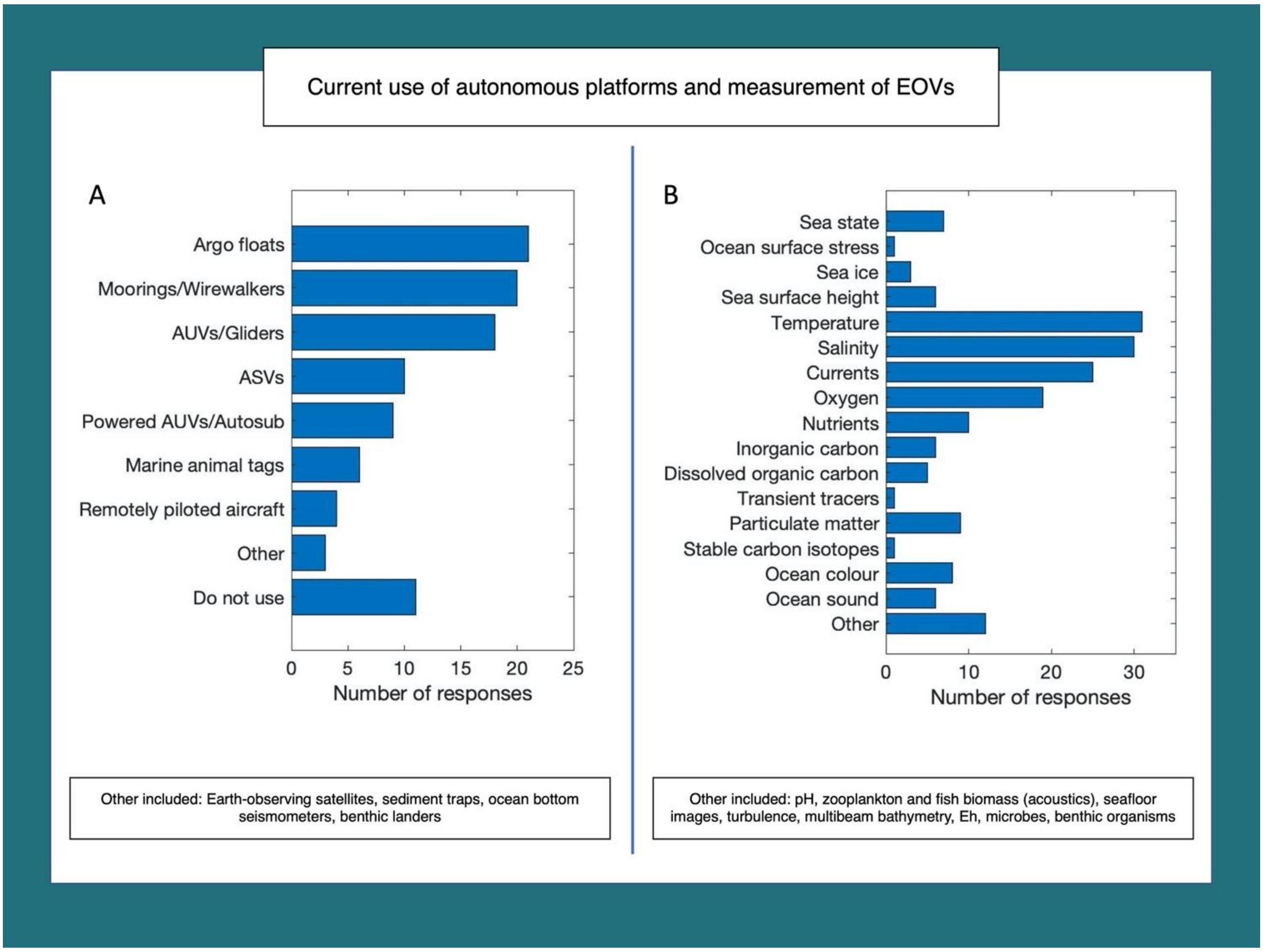


Figure 7: [Top] Number and changes (over the last 5 years) of cruise locations from an automated search of reports in BODC; [Bottom] Changes (over the last 5 years) of observation keywords from an automated search of reports in BODC for all cruises and for the North Atlantic only (Brannigan, 2021)

Online survey results

A significant proportion of the 44 survey respondents have used autonomous platforms (including AUVs: 39%, profiling floats: 47%, RPAs: 11% or ASVs: 26%) in their research, with the majority using them to measure ocean temperature, salinity, currents and oxygen, and a smaller number using them for nutrients, particulate matter and carbon (see Appendix 4 for survey report). The important advantages of the platforms were identified as long endurance, high sampling frequency, and high data quality. Less frequently identified as important were low cost, real-time data access, and the existence of a global network (Fig. 8).


Current use of autonomous platforms and measurement of EOVs

Other included: Earth-observing satellites, sediment traps, ocean bottom seismometers, benthic landers

Other included: pH, zooplankton and fish biomass (acoustics), seafloor images, turbulence, multibeam bathymetry, Eh, microbes, benthic organisms

Figure 8: A) Current usage of autonomous platforms, and B) Current Essential Ocean Variable (EOV) measurement, according to WP1 Survey.

Oceanographic publications

Survey of all oceanographic publications

A survey of all UK-based[11] oceanographic papers from some of the key journals in the field reveal that there has been an increase in publication outputs of science using autonomous technology over the last five years (Brannigan, 2021). However, this increase is seen more clearly in journals specialising in physical oceanography, as compared to biogeochemistry, likely reflecting the more recent (and evolving) emergence of chemical sensors. Over the last decade there has been a fall in the number of UK publications centred on observations from the Atlantic, most notably seen in data from the *Journal of Physical Oceanography*, although the region remains the most published about basin. but a general increase in publications about the Southern Ocean (Fig. 9-10).

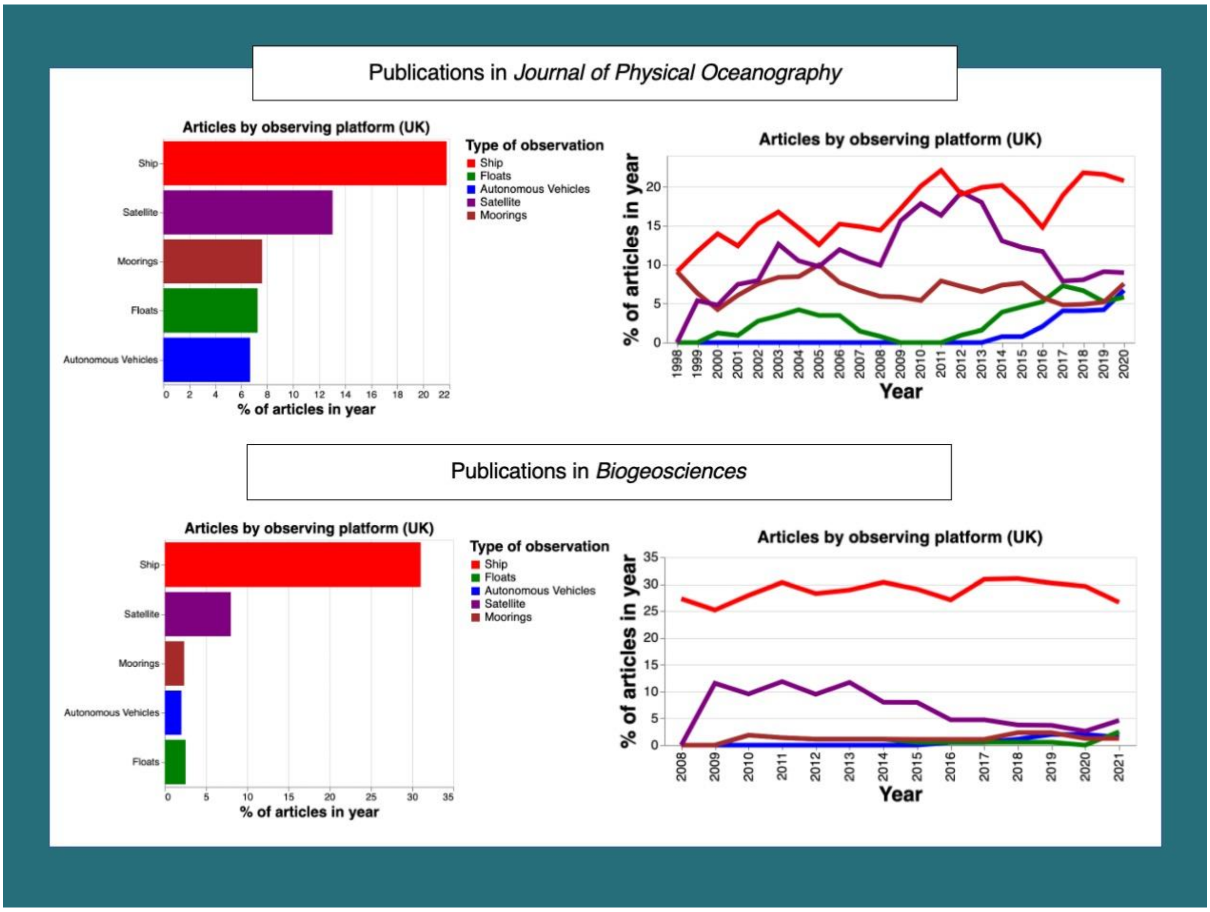


Figure 9: UK-based publications from Brannigan (2021) from *Journal of Physical Oceanography* and *Biogeosciences*, categorised according to the technology used.

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[11] Defined as a publication that has at least one UK-based co-author

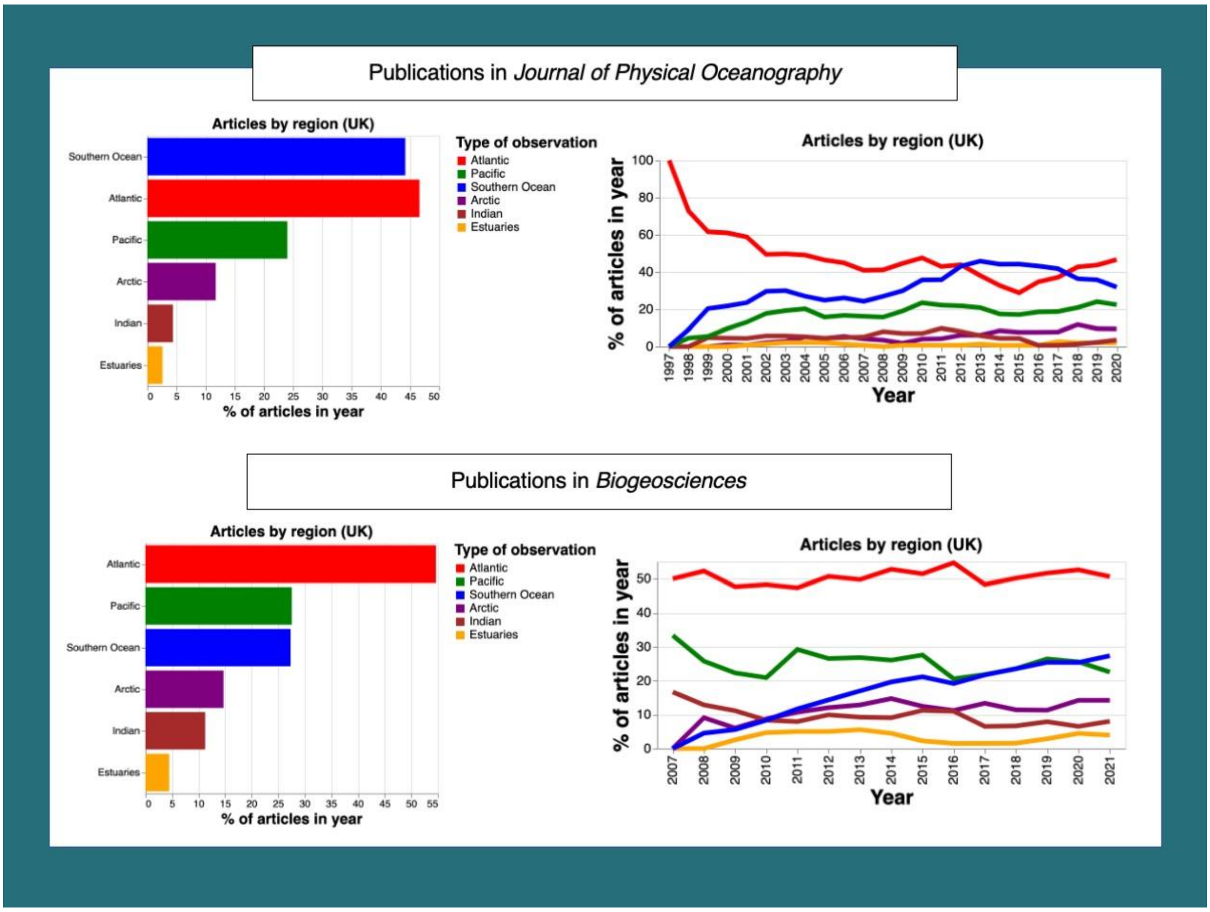

Figure 10: UK-based publications from Brannigan (2021) from *Journal of Physical Oceanography* and *Biogeosciences*, categorised according to geographical location of observations.

Survey of publications referencing expeditions on NMF and BAS ships

An investigation of publications either acknowledging ships and codes, or long-term datasets, reveal two routes for maximising impact of a cruise (Table 3):

i) projects with large number of high-impact papers referencing the cruise number (generally larger, process-based strategic NERC grants e.g., Shelf-Sea Biogeochemistry and Changing Arctic Ocean, or large-scale EU funded projects);
ii) long-term monitoring projects that feed into high-impact datasets (e.g. PAP, AMT).

Note that this survey only investigated academic peer-reviewed publications and not other forms of impact, e.g., PhD and Masters theses, reports, non-peer-reviewed outreach and education publications.

Cruise code	Year	Project/funding	Publications (all)	Publications (Impact Factor >2)
DY077	2017	PAP	5	4
JC132	2016	NERC	5	4
JC136	2016	NERC (DEEP-LINKS)	5	5
JC138	2016	Blue Mining	5	5
DY081	2017	EU	7	7
JC142	2016	NERC (SoS Minerals)	8	8
DY021	2015	NERC (Shelf-seas)	9	9
JR15005	2016	SO-AntEco	9	4
JR16006	2017	NERC (Changing Arctic)	9	9
JC114	2015	NERC (OSCAR)	9	8
DY030	2015	NERC (Shelf-seas)	10	10
DY034	2015	NERC (Shelf-seas)	10	10
JC124/JC125/JC126	2015	EU	10	9
DY033	2015	NERC (Shelf-seas)	11	11
JC120	2015	EU	14	12
DY029	2015	NERC (Shelf-seas)	15	15
PAP*			50	45
AMT*			79	76
RAPID*		NERC	80	(9**)

Table 3: Cruises with more than 5 associated peer-review publications; *denotes citations using long-term datasets maintained by the PAP, AMT and RAPID projects. **9 publications described by Web of Science as being in the top 1% of all geoscience publications. Survey carried out February 2021.

Horizon Scan & Transformational Technology

The horizon scan for 2020-2035 attempts to summarise some of the key points for sensor, platform and data requirements for a future reduced carbon approach to oceanographic observing. In doing so, we have addressed perceived shortcomings in the current autonomous capability, as well as anticipated shifts in workings patterns to handle current and future increases in data volume. New technologies were identified to build a flexible and adaptable observing system that has the capacity to react as science questions change. They roughly fall into the categories of sensor development, platform development, data ecosystems and telemetry, though there are also linkages between these categories.

Sensor development

New developments in sensors are already underway, offering the potential to observe more parameters more quickly and on remote platforms. These and further developments in sensors will improve our ability to measure the oceans with reduced reliance on laboratory-based analyses. However, it is important to note that for some applications, these laboratory-based methods using standardised reference materials provide useful calibration points for the existing autonomous approaches to marine observing, including for Argo and for Earth observation.

In order for new developments to be maximally useful, the sensors must be trialled, tested and demonstrated in the real-world applications to satisfy science requirements; such validation can take several years from start to completion and must be taken into consideration in the context of the Net Zero timeframe (Fig. 11). We note from the survey of UK marine scientists, access to sensors was seen as a barrier to uptake (see Barriers to uptake of autonomous technologies). For international ocean observing (largely, sustained observing systems), some of these requirements are well-specified. Experimental observing may have different requirements, and these requirements cannot be known at this time.

The 2035 data requirements discussion at the NZOC Workshop 1 identified required areas for sensor development, including:

- Improvements to data quality, particularly for sustained observing purposes. For example, WOCE requirements for temperature are accuracy to +-0.002 deg C, salinity +-0.002 PSS-78, and pressure +-2 dbar.
- Expansion into a wider range of EOVs and integration with autonomous platforms.
- Simultaneous measurements of multiple parameters. At present, individual autonomous platforms typical measure a small subset of EOVs. BGC-Argo identified six core variables in addition to CTD: irradiance, suspended particles, chlorophyll-a, oxygen, nitrate and pH (Bittig et al., 2019).

All of these requirements would need to be met in order to fully replace existing oceanographic capability with an autonomous approach. In addition, it is not possible to fully anticipate future science needs.

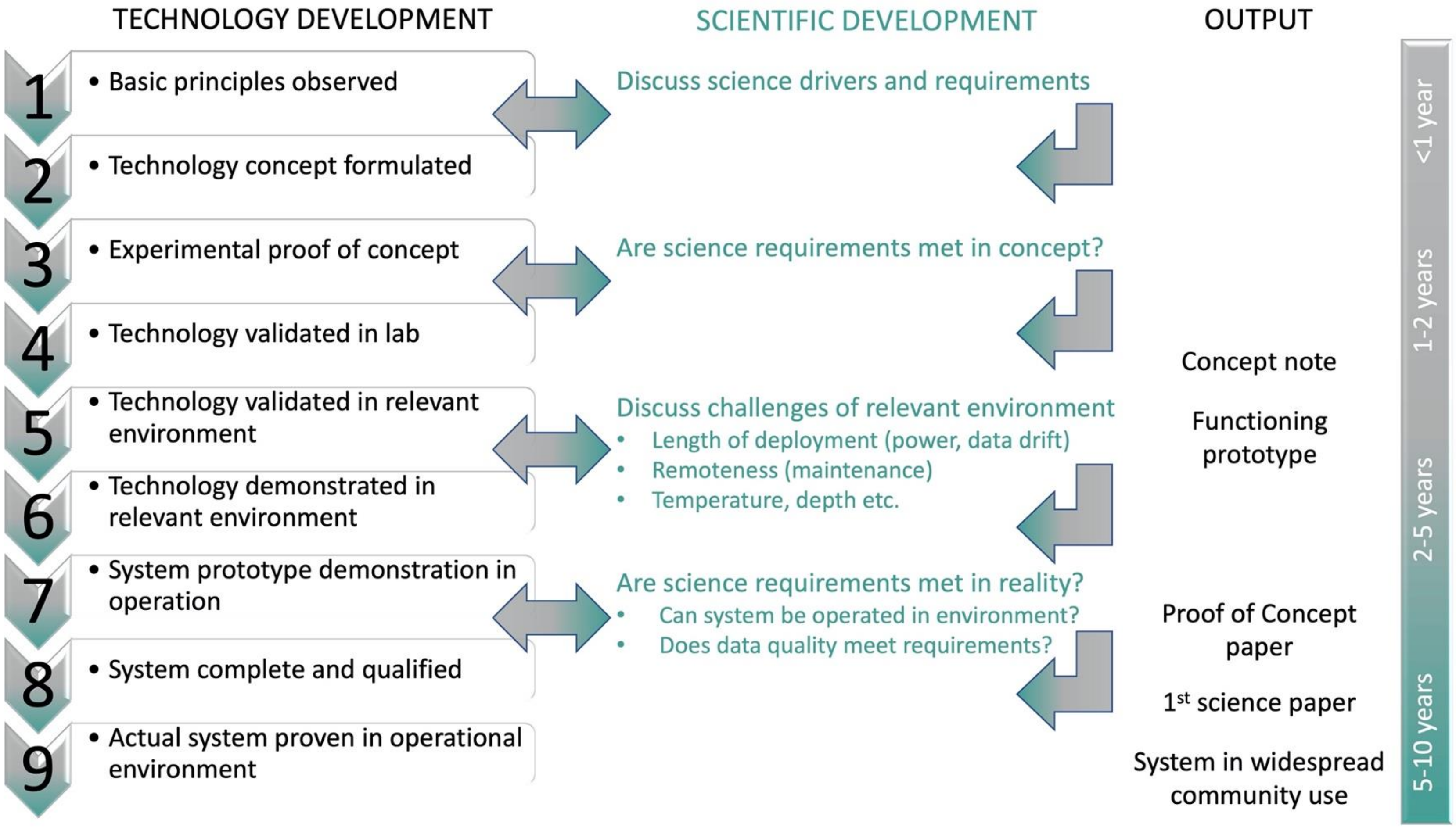

Figure 11: Technology Readiness Levels (TRLs as defined by Horizon 2020[12]) in the context of a novel marine sensor, with embedded technology developments and scientific discussions, and suggested timeframe of scientific outputs.

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[12] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf [*accessed June 2021*]

Areas where new or improved sensors could transform the scientific application are outlined below.

New sensors: Physics. Temperature, salinity and pressure have been measured by electronic sensors for some time. While these measurements are routine, the process by which the electronic sensor data are translated into high quality data, still relies on ship-based calibrations (salinometers) to ensure that drift or damage to sensors has not taken place. For climate applications, the data accuracy is of high importance, otherwise the relatively small signals of e.g., ocean warming that are spread over very large areas, cannot be distinguished from no signal. In order to replace hydrographic sections with autonomous platforms carrying sensors, the data quality requirements must be met. WOCE requirements for temperature are accuracy to 0.002 deg C, salinity 0.002 PSS-78, and pressure 2 dbar. This is achievable, but still outside the current capability on autonomous platforms. However, the benefit would be large, of replacing ship-based measurements in this particular, routine application by an autonomous approach. The technology solution might include self-maintaining/cleaning and calibrating sensors for these fundamental measurements. Some work is already underway within the deep Argo community, working with instrument manufacturers, to improve commercial CTD sensor quality.

New sensors on autonomous platforms: Biogeochemistry. Biogeochemical measurements in the ocean are traditionally made by taking water samples and then processing them in the lab. Current developments are underway to produce electronic sensors including of key nutrients (nitrate, phosphate, silicate, iron) and carbonate parameters (pH, DIC, TAlk). These sensors have the potential to revolutionise the field of biogeochemistry, enabling high resolution (resolution matching physical measurements) of carbon and nutrients which would underpin new process-based understanding of how these parameters evolve in the ocean. However, at present and for some parameters, the limits of detection are not sufficiently low to measure changes in the deep ocean. Commercially-available sensors still suffer from issues such as instrumental drift, meaning that the data cannot be used without ship-based measurements for *in situ* verification using traditional approaches. Most of these sensors only measure dissolved quantities which limits mechanistic understanding of biogeochemical processes, and thus their integration into earth system models. A further development would be required to measure particulate organic matter (or microplastics), perhaps using acoustic techniques that would bring the sampling in line with remote sensing techniques used in the atmosphere. Without such sensors, ships would still be required to make measurements of particulate organic matter.

New sensors: Biology. Biological monitoring and sampling are more challenging than physical or biogeochemical measurements, but are required to understand biological indicators of change in individual organisms, species or populations, and to understand changes in habitats. At present, sampling occurs through taking samples of organisms and processing them on ships, which is time and labour intensive, and results in small datasets. Transformational technologies in support of these studies could include expansion of eDNA approaches, tagging methods, use of taxonomic and DNA libraries/bar-coding, photography/imaging (including automation of digital imagery driven by in-glider AI in order to target specimens), Passive Acoustic Monitoring (PAM), high-resolution satellite data, use of adaptive sampling. For sampling organisms for later processing in the lab, there would need to be a means of *in situ* preservation to ensure the sample does not degrade before the lab processing can be completed. 'Omics' technologies could be also transformational for determining rates of biological processes and organism interactions/behaviours, which has to date been more challenging.

New sensors: Geology and geophysics. Imaging, profiling, and sampling of sediments and seafloor rocks are used to understand the present-day geophysical condition, as well as past climate. These methods target a variety of sediment and rock types and conditions (contourites, vent sites, abyssal plains, coastal and continental shelves, etc.) and are accomplished through drilling, cores and grabs.

Transformational technologies to support sediment studies could include *in situ* measurements of microbial activity (e.g., eDNA), porewaters (nutrients, metals, dissolved organics) and dissolved gases (methane, hydrogen sulphide). Seismic reflection and electrical resistivity methods for soft sediments could be deployed from automated landers, needing a range of frequencies for a range of resolutions and penetration depths (potentially increasing depth of penetration beyond what it currently possible).

Sampling of sediments would require a means of *in situ* preservation (using different preservation methods e.g., pressure and temperature control, freezing, anaerobic conditions etc.). Solid earth geophysics could be advanced through robotic deployment of ocean-bottom seismometers (OBS), resistivity meters, or AUV-towed streamers. Subseafloor coring and drilling (wireline) could be improved to sample and log currently challenging materials e.g., hard/broken/fractured rocks, sands, gas hydrates. Seafloor holes could be used for observatories and experimental stations (microbial, chemical, mineral stability, deformation, high T and high P, eH, pH extreme environments that are difficult to replicate in laboratory).

We note, however, that it is unlikely that deep rock drilling (1-2 km below the seabed) will be feasible by autonomous means within the Net Zero timeframe. Given the power requirements for dynamic positioning, with present technology it would be challenging to replace the International Ocean Discovery Program ship with a green ship. Additionally, given that there are only a very limited number of these ships in use for science (fewer than 5), it seems unlikely that it will be worthwhile to develop the technology to accomplish this in a Net Zero approach in the near term.

Platform development

Areas identified for technological development associated with autonomous platforms centred on two areas – addressing the expansion in data volume, and maximising the ability of autonomous platforms to work in challenging environments.

- **Data volume:** Anticipated increases in the use of autonomous platforms mean that command and control of those platforms, and data handling will both require scalable solutions. For data handling, best practices are needed for generating meta data, data quality control and quality assurance, and effective solutions to enable access to high volumes of data.
- **Position information:** A current limitation of autonomous underwater platforms is their inability to self-locate. Development is needed in geographic (lat/lon) positioning of subsurface data from autonomous platforms in order to maximise the value of data. This is needed whether the platform is in the open-ocean or under sea-ice, near the sea-bed or mid-water column.
- **Depth-rating:** Autonomous underwater gliders are currently limited to 1000 dbar. In order to replace e.g., hydrographic sections with gliders, they must be able to make full-depth

measurements. Most Argo floats are limited to 2000 dbar, but there are an increasing number of floats within the Deep Argo program (6000 dbar) to cover most of the full depth range of the ocean. Deep Argo floats numbered 69 out of the 4000 functioning Argo floats in 2018, with plans to increase this to over 1000 by 2018 (Roemmich et al., 2019).

UK marine science requirements were also identified that are unlikely to be achieved through the use of current or anticipated autonomous platforms and sensors. These included GO-SHIP decadal hydrographic sections which require simultaneous measurement of a wide range of parameters (CTD, sensor oxygen; bottle salinity, oxygen, nutrients, CFCs, and 2 of DIC, TAlk, and pH; surface and subsurface velocities; as well as meteorological data[13].), deep sediment and rock coring (e.g., IODP), measurements of rates (e.g., primary and secondary production, respiration), and biological sampling including identification of in the water column and at the seabed. While deep rock coring does not currently take place on NERC research vessels, the other science requirements are unlikely to be met through autonomous solutions by 2035.

The use of autonomous platforms including profiling floats, gliders, autonomous surface vehicles, remotely piloted aircraft and both smaller and larger autonomous underwater vehicles have been proliferating in the recent 2 decades.

Relative to traditional ship-based measurements, autonomous platforms can enable high resolution data (in time, in horizontal resolution or vertical resolution, or both), near real-time data transmission (sending data back via satellite), longer endurance studies (gliders can survey for many months), and access to remote environments (including the open ocean) or harsh environments (including wintertime seasons and near or under ice).

Platforms enabling high-resolution data: Physics. Ocean physics studies require the measurement of temperature and salinity, pressure and currents. Measurement technologies have existed for decades. However, beyond knowing the properties at a single location, the application of physical laws requires knowing the spatial and temporal gradients in these properties, e.g., how quickly seawater density changes with depth or horizontal location. Understanding of ocean physics would be transformed by being able to measure the properties and velocity at all points, akin to knowing the values in every grid point of a model, which would enable smooth derivatives (d/dx, d/dy, d/dz, d/dt) to be computed. Whilst technology to do this is unlikely to become available, there are emerging approaches (e.g., swarms of autonomous platforms) that could enable targeted areas of high-resolution data collection (from 10s of meters to 1 km horizontally) that would enable process-level understanding of ocean physics, provided that sensor data were sufficiently accurate to allow for derivatives to be calculated between platforms. At the sea surface, high frequency radar has been used for decades to provide meter-scale surface currents, while acoustic tomography can be used to determine the internal structure of ocean temperature and currents at basin scales (Dushaw, 2019).

Subsurface, measuring spatial gradients presents unique challenges to sampling platforms. In order to calculate terms in the equations of motion for the ocean, spatial gradients are needed. Data must enable the calculation of spatial gradients (dC/dx, dC/dy, dC/dz) across small changes in time (i.e., before the ocean has changed to a new local state). This requires data of sufficient precision relative to local signals of change (that dC be measurable, i.e., sensor accuracy is sufficient to resolve the change), as well as targeted sampling patterns to make measurements at the same depth but some

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[13] https://www.go-ship.org/DatReq.html [*Accessed April 2021*]

distance apart horizontally (d/dx at a constant depth and near instantaneous relative to the d/dt of the ocean process).

Platforms enabling sustained observations: Physics. Transformational technologies required to support replacement of GO-SHIP hydrographic sections with autonomous gliders are primarily in the area of data quality (see Sensors) and in the ability to measure multiple parameters simultaneously. GO-SHIP hydrographic sections are our primary method of observing deep ocean properties (temperature and salinity) and are critical to understanding the planet's energy imbalance, the storage of heat in the deep ocean, and the regional and global patterns of sea level rise. At present, these transects are repeated once every decade (full suite of measurements, including tracers such as CFCs and biogeochemical parameters) but some section are also repeated more often with a limited set of measurements. It is conceivable that these higher frequency repeat sections could be replaced by autonomous underwater vehicles, reducing cost and data latency, but only if the data quality can be improved (WOCE requirements for temperature are accuracy to +-0.001 deg C, salinity +-0.002 PSS-78, and pressure +-2 dbar) and the depth-rating of the vehicles expanded to reach the seabed.

Platforms enabling data at interfaces. Key processes at the air-sea interface remain undersampled. These include fundamental processes such as heat and gas fluxes (how much heat does the ocean release? Take up? How much carbon is stored in the ocean?). Some of the lack of data is being addressed by instrumenting ships of opportunity (voluntary observing ships), but these are limited to the planned tracks of the ship. Autonomous surface vehicles such as Saildrones represent a transformational technology for measuring at the air-sea interface following the 'data as a service' model. This approach provides flexibility, but at a cost specified by the provider. If data quality and platform reliability are sufficient, they could be used for automated measurements of key parameters in regions that are unlikely to be accessed by ships of opportunity (Southern hemisphere, polar regions). They might also provide a platform for: mounting cameras and optics sensors (e.g., for identifying plastics); efficient, low-energy means for sample transport (samples of water, sediments, other) from "repositories"; for data telemetry solutions to recover data acoustically from sub-sea infrastructure (e.g., moorings); or to transport slower autonomous underwater vehicles (e.g., gliders) to or from sampling regions. However, this data as a service approach may limit the scaling up of the solution depending on the provider's capacity, and may also limit whether the vehicles can be used in higher risk environments.

Data ecosystems: Accessibility, Data science and Telemetry

Data access: At present, there is a key deficiency in data access. There are ongoing developments (see WP6 report) in improving the current national repository, British Oceanographic Data Centre, including to align better with FAIR principles (Findable-Accessible-Interoperable-Reusable). These should include the capability to search for data of interest by geographic region, instrument and measurement type, time period and platform, with data downloadable in common, documented formats for easy machine readability. Current issues with data access will be exacerbated by increases in data volume. With the increase in data from autonomous platforms, the data solution must be scalable as well as account for decreased latency from data being deposited to data being accessible. This was highlighted in the WP1 workshop, but also further addressed in WP6.

Data science: Machine learning or AI development and integration with automated platform, sensor and sampling technologies would allow for easier and quicker ocean data availability and add potential to the goals of efficient/smart/optimised planning and observations, real time monitoring at a range of spatial scales, and rapid quality control. Data centres could be established with links to remote telepresence for understanding ocean observations as they happen, allowing intelligent filtering tailored to personal interests and expert intervention in subsequent observations with made autonomously or by operators in the field. AI could also be used for more effective mining of existing data, and aggregation of different data streams through time for a particular location. This topic is also addressed in WP6.

Telemetry: At present, data are typically measured on ships or in situ by installed sensors*,* and then recovered and deposited sometime after the fact into national repositories. Telemetry has many benefits, including data safety, early knowledge of instrument failure (enabling replacement efforts to be undertaken) or ingesting data into operational forecasts. The use of data for operational oceanography and weather forecasting has led to e.g., the Argo profiling float array and the Global Drifter program. These two observing networks provide near-real time, near-global coverage of ocean properties in the upper ~2000m (standard Argo) and at the surface (drifters). Gliders also send back their data in near-real time.

Further development in telemetry could enable more regular access from other methods of observing, allowing for data harvesting from subsurface assets by autonomous platforms and providing near-real time access to long term monitoring efforts. Above water, data transmission standards are relatively widely used based on the Iridium satellite system. For underwater transmission, development would be required to integrate transducers into autonomous platforms, as well as to define protocol for the data format, transmission (e.g., in noisy environments or handling partial transmission).

Stakeholder data requirements: Modelling community

Outputs from sustained observing including GO-SHIP, Argo, RAPID and other programmes are used in model initialisation and validation. However, parameterisations in models – including representation of sub-grid scale physical processes, processes at interfaces (air-sea, sea-ice), and of biological and biogeochemical processes – can meaningfully impact the evolution of the large-scale state of the simulated ocean (Danabasoglu et al., 2014). Inaccuracies of model representation of these processes can result in biases and tendencies relative to the real ocean.

Observational programmes could benefit from better connections with the modelling community in order to plan sampling, including efficient use of ships, autonomous instruments and remote sensing. Models have already been used to inform observing systems (e.g., the WOCE and Argo profiling float program), but this continued interaction would be mutually beneficial if the model used to plan observations is sufficiently realistic in the area of interest. This is particular the case when a high-resolution four-dimensional view of the oceans (and atmosphere) is needed: full observations may not be possible (even with autonomous technology) requiring a flexible and adaptive sampling strategy. Similarly, measurements could be targeted at model uncertainties and potential feedback processes, especially in relation to processes and interactions. All data streams (observations and models) could then be integrated and made end-user friendly.

Interconnection of Different Technologies

While the transformational technologies above were mentioned individually (a platform, or a sensor), co-development between technologies will be required to maximally benefit from new technology and to ensure fit-for-purpose between platforms and sensors.

- Swarms of remotely-piloted or autonomous vehicles
- Data science to plan missions or update missions in near real-time
- Use of new sensors on autonomous platforms
- Data safety
- Power

Swarms of remotely-piloted or autonomous vehicles. Swarms of remotely piloted or autonomous vehicles would expand the already high resolution of data available from these vehicles[14]. A higher density of vehicle deployments might also allow for hub-based charging (with a vehicle 'docking' at a charging hub to extend endurance). Recharging "hubs" could also be used as data caches to increase data safety. Such swarms could also be used in tandem with traditional ship-based observations, expanding the footprint of the sampling while leveraging the high quality, calibrated data from the ship to remedy data quality issues from autonomous platforms. At present, it is not clear whether autonomous underwater vehicles have been used in tandem with remotely piloted aircraft. Such cross-platform swarms could be useful for better understanding connections at the air-sea interface, but would require some attention to how to meaningfully match the different platform speeds and capabilities above and below the sea surface.

Command and control would need to be scalable to allow meaningful data to be retrieved, but it is not yet clear whether there are common 'types' of sampling patterns that would be of value. Adaptive sampling methods could be developed for intelligent sampling, where the vehicle has some awareness of its scientific mission. Safety would be increased if hazards could be avoided by the vehicles. Dormant technologies (i.e., "waking" unpowered AUVs waiting in a particular location, using a signal) could also be used for the efficient observation of a specific event. This would allow the real-time monitoring of events at large scales connected to high resolution swarming systems that can be deployed quickly to explore a particular process.

Multi-functional autonomous systems vs Targeted systems. To enable process-type observations, there is a need to shift away from "one size fits all" platforms and sensors design constraints, towards re-deployable, multi-functional observation systems that can go to a location to perform different tasks (i.e., become full laboratories). It is important to develop systems that can be tailored to specific observation needs (subsurface probing, or deep ocean, or under ice) without making them bespoke to the extent on being single user systems. These systems would be high power, high bandwidth, and high complexity platforms, but could be long-lasting and run on renewable energy and efficiently using smart technologies.

However, for well-defined and global-scale observing applications (e.g., autonomous replacement of GO-SHIP hydrographic sections), it may be that a targeted, single-purpose, low cost system would better meet the programme goals. As GOOS has global-scale goals requiring dozens of basin-scale

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[14] e.g. OASYS project https://uni.oslomet.no/oasys/ [*Accessed May 2021*]

ship-based transects, the need and carbon-savings of autonomous replacement may be sufficiently great to justify investment in a single- or limited-purpose observational platform. This development would need to be in consultation with the GO-SHIP community to ensure the engineering solution is fit-for-purpose (and thus would be accepted by the community).

Data safety. One of the risks of moving towards autonomous platforms as a primary source of data collection is whether or not the platform will be recovered. If the platform is not recovered, and the full dataset is transmitted in real-time, then data are 'safe'. However, autonomous platforms can also be used to recover data from other sensors including on subsurface moorings or as localised hubs for swarms of vehicles. For example, Saildrone-like autonomous surface vehicles could be used as an efficient, low energy means for sample transport from repositories or hubs for recharging other vehicles. Recharging "hubs" for fleets of underwater vehicles could be used as data caches to ensure data redundancy in case an individual member of the fleet fails and is not recovered, or to simplify the process of recovering data from a large fleet of vehicles.

Power and energy. One of the current limitations of autonomous platforms (e.g., Argo floats and gliders) is in their power limitations. At present, most are limited by the battery capacity at deployment. New technologies are coming online including thermal batteries which recharge themselves by moving through thermal gradients in the ocean and for systems with low power requirements (floats and gliders) can provide a near inexhaustible source of energy[15]. Solutions such as this, or new batteries, recharging technologies or platforms will enable yet greater benefit while minimising the carbon cost (or other environmental cost) per datum.

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[15] https://seatrec.com/products/ [*Accessed May 2021*]

Gap Analysis

The use of novel sensors, autonomous platforms and other emerging technologies are going to be critical in adapting UK marine science approaches to meet the UKRI Net Zero pledge. The widespread use of autonomous platforms is a recent phenomenon, with floats having been used for some decades, and gliders only coming into common use in about 2007. Since then, the UK marine science community has been publishing papers using autonomous vehicles at a rate of 2-3 times higher than the global average (i.e., 5-7% of UK marine science papers published in the *Journal of Physical Oceanography* or *Journal of Geophysical Research* use autonomous vehicles, whereas globally only 2-3% of the papers published use autonomous vehicles). Uptake of new technology has been rapid, and across the global marine science community, the use of autonomous vehicles in marine science is increasing (Fig. 14-15). This demonstrates the increasing use of gliders in physical oceanography. For chemical and biological oceanography, where sensors were developed later, the use of autonomous vehicles is still rare. However, the expansion of parameters being measured on BGC (biogeochemical) Argo floats and particularly with the large US-funded project SOCCOM in the Southern Ocean and the recently US-funded global BGC Argo array (GO-BGC), the usage of floats for non-physical measurements has been expanding. There is a current gap, however, in the use of these sensors on autonomous vehicles rather than floats. This gap could be filled through over-coming barriers relating to technological development, quality control and trust in data through expanding resources for BGC sensor development, including additional parameters, together with quality control, calibration and ground-truthing.

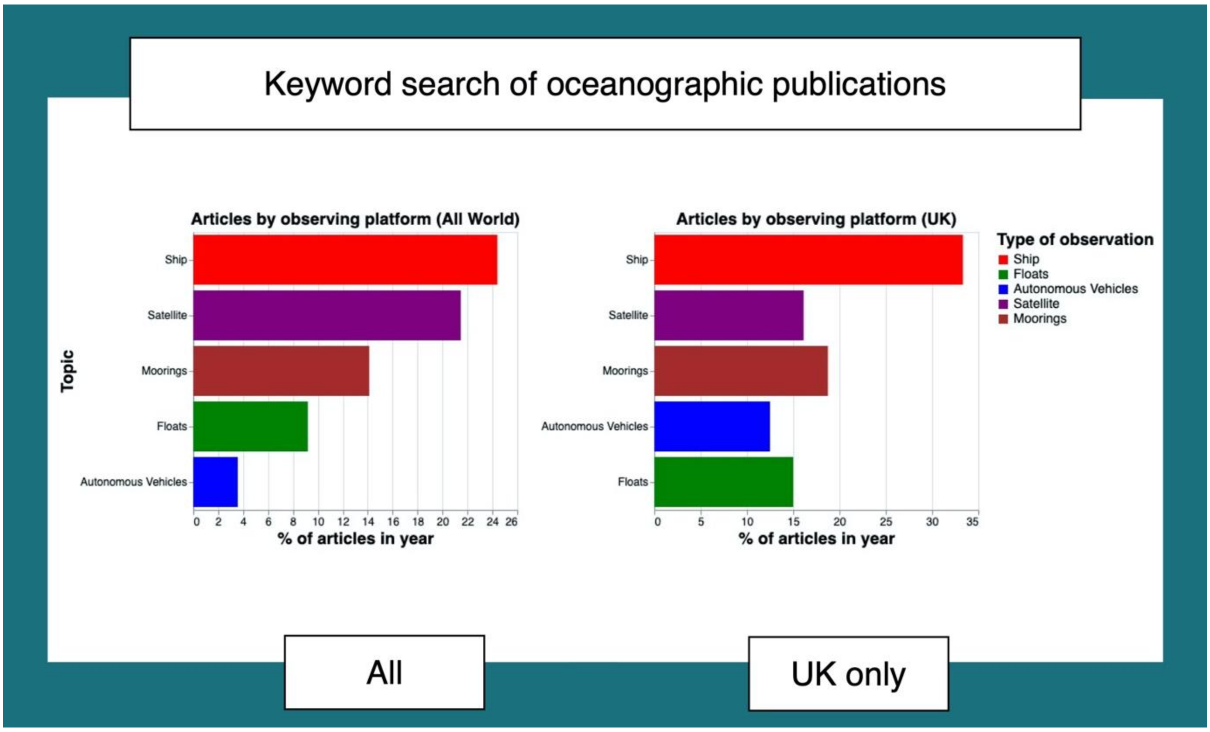

Figure 12. Articles published in the *Journal of Physical Oceanography* in the past five years, showing the observing platform used for (left) all papers and (right) papers with at least one author in the UK.

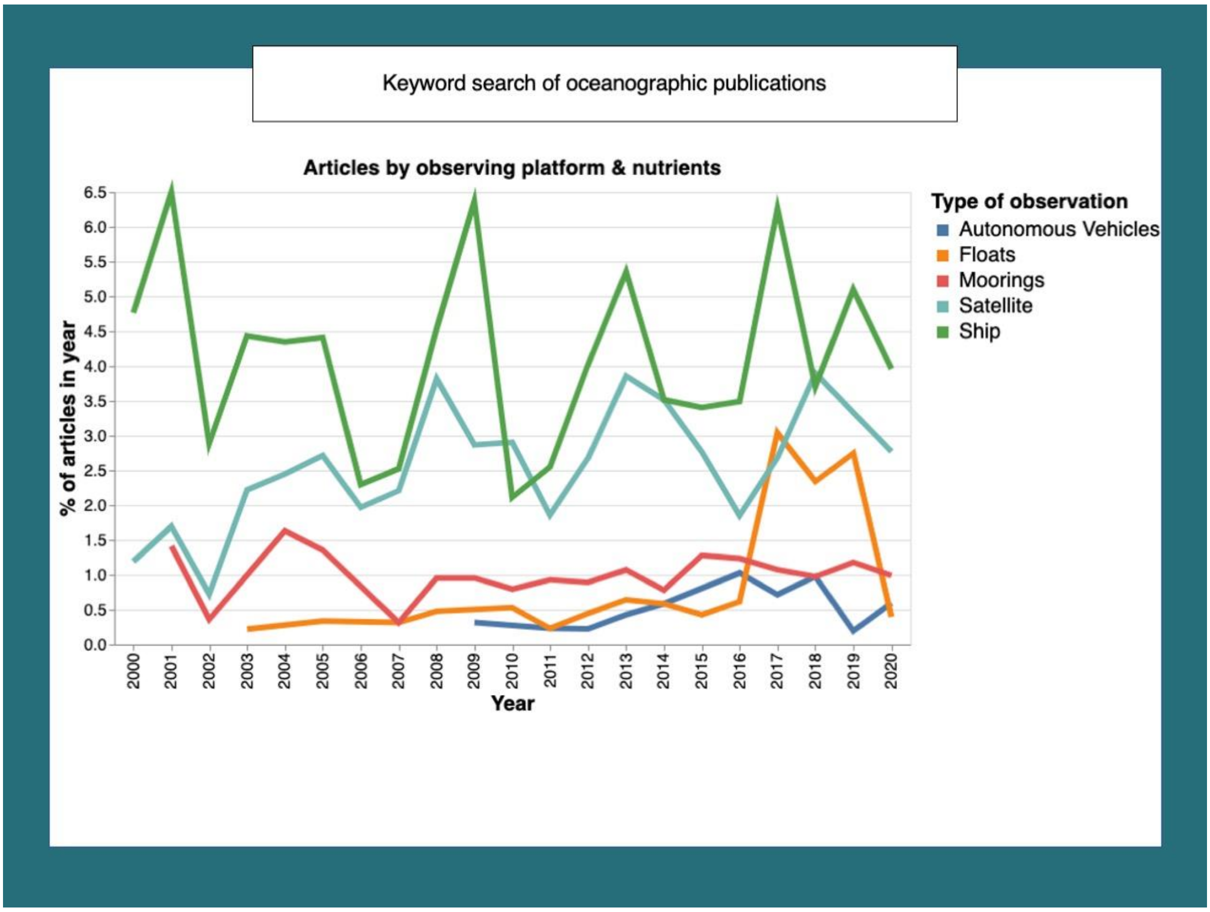

Figure 13. Articles published in the *Journal of Geophysical Research Oceans* using different platforms and measuring nutrients.

Barriers to uptake of autonomous technologies

In the above sections, we detailed opportunities for development to provide the UK marine science community with transformational technologies, including platforms, sensors and data science tools. Some of these sensors may not be possible to develop within the near-term, and there has been no community survey or other effort made to prioritise which sensors are most critical. Some developments may be more tractable in the near-term, with others having no clear path forward. There are also more routine measurements that have been identified in the sustained observing strategies (See Ocean observing strategies) that are likely to be widely used and continued, though the scientific outcomes will be more distributed. Prioritisation will be a challenge, and it is not clear how this should be done, whether based on the tractability of the technological problem, on how widespread the anticipated usage is, or on how high impact the anticipated scientific outcomes might be.

There are benefits to wider access to routine sensors, but also a risk to limiting the lab-on-a-ship approach that enables a wide range of laboratory-based methods that must first be established, tested and accepted by the scientific community, before attention can move to developing a sensor. These latter approaches are a significant part of what makes the UK world-leading in marine science: developing new methods and asking questions which cannot be answered using off-the-shelf sensors or platforms.

The “lock-in” concept and UK marine science

The “lock-in” concept is used widely to explain the persistence of problematic or suboptimal institutional or technological systems, which could additionally block the advancement or adoption of emerging technologies and approaches (Klitkou et al., 2015). Identification of the relevant lock-in mechanisms relevant to transition pathways – largely relating to the complex culmination of knowledge, skills and organisation within the marine science “ecosystem” – is key for minimising barriers to adaptation.

Examples of potential lock-in categories (adapted from Klitkou et al., 2015) in marine science include *institutional learning effects*, essentially where complex knowledge and skills cumulate through the evolution of methodologies (“process X has always been done this way, and we know how to do it well”); *informational increasing returns*, where particular technologies or approaches gain greater attention through promotion, for example, in high-impact publications (“Group or Laboratory Y do it this way, so we should too”); *network externalities*, where particular approaches are used to be consistent with other national or international groups (“if we do it a different way, our data will not be comparable with any other group”); *collective action*, where ‘norms’ or customs emerge (“the community agrees that process X should be done this way, and no one will believe us if we try a different way”).

One specific example of a possible ‘lock-in’ situation is global Argo float array. At present, Argo floats are an economical way of measuring ocean properties (temperature, salinity) in the top 2000m. However, they are not designed to be recovered and end up on the seafloor (roughly 750 floats per year). While this is an acceptable near-term solution, in 100 years the accumulation of litter may no longer be acceptable. The availability and low cost of Argo floats means that resources are put into maintaining the Argo array, rather than into developing an autonomous vehicle that could supply the purpose of the Argo array, but would be recoverable at end-of-life.

Survey results on barriers to uptake of autonomy

Below we outline some of the other identified barriers to uptake of autonomy in marine science, which fall into one or more of these categories, with suggestions as to how they can be overcome through flexibility, parallel ground-truthing studies, and training.

From the survey of marine scientists, 47% of respondents identified that the inability of autonomous platforms to measure their parameter of interest was a barrier to further uptake. This issue was expanded in the workshop, with the ‘sensors’ sections above outlining areas where developments could be made. Also from the survey, 29% of respondents noted that they could not move to using autonomous platforms because it would disrupt the continuity of long-term datasets. This issue was also discussed in the workshop, highlighting the need for overlap between traditional approaches and new approaches to safeguard the value of these records. Smaller proportions of respondents identified poor reliability, calibration and accuracy, access to technology and cost as barriers to uptake. In querying marine scientists about what it would take to get new sensors into more widespread use, a majority identified that the primary area for improvement would be access to the sensors (‘availability or ease of access’) with 63% of respondents citing this as a barrier. Other identified barriers to using new sensors included ‘reliability’ (60%), and accuracy, precision or calibration (47%).

The online survey also identified potential barriers specifically relating to achieving low carbon approaches, including the continued need for biological sampling (39%), use of moorings (27%), shipboard incubations (27%) and sediment coring (25%), in addition to isotope analyses, satellite launches, and experiments. Sampling, adaptability and high power requirements were all identified as aspects of your fieldwork requirements that will present challenges to Net Zero objectives.

Barriers identified by respondents also included

- “poor reliability/confidence or means to ascertain correct procedure has been carried out”
- “platform cost”
- “cost/access to technology in the first place; feels like guarded territory”
- “depth rating and locational precision for deep water outflows”
- “limited ability to make real-time adjustments to sampling strategy”
- “cost – we could replace shiptime, but need to find new money on top of shiptime”
- “platform range – need to map areas far from shore”
- “gliders more costly than I had assumed and also only measure a handful of variables”
- “cannot reach abyssal unexplored environment”
- “lack of real-time communication capability”

We note that the survey represents only a sample of the UK marine science community, and may be skewed towards individuals who already have an interest in autonomy.

Data science skills

With the shift in approaches to carrying out sea-going research – the “ecosystem” of UK marine science – there is likely going to be an evolution in the career path of marine scientists. Whilst further work needs to be done to assess the likely impacts on researchers in different sectors and from all career stages, it is clear that skills training is going to be essential to adapt to new and emerging technologies.

There is a clear need to adapt marine technician training to encompass the emerging technologies discussed in this report, including the deployment of platforms and use of sensors. But there will be an ever increasing need for marine scientists to be able to transition current working practices to handle larger volumes of data coming in from autonomous platforms. UKRI has pledged to reach Net Zero by 2040. At this time, assuming a 40-year working career, many of the current marine science workforce will still be in post. They will require, as will the new marine scientists, training in order to transition successfully to a new working model.

Where do the gaps exist?

Marine scientists already trained, for the large part, in transferable skills (collaboration, adaptability, communication), but may need additional training in some technical skills (analytics, AI, lifecycle and quality management, modelling, security and ethics). Many marine scientists are already data “producers” and “consumers”, but don’t necessarily identify with these roles, and so do not accept the associated responsibilities. More data awareness training for all marine scientists will be essential to ensure good data management practice and effective collaboration with data centres.

In addition to general training, the following data specialist roles will also need to be considered[16]:

User researchers to assess who the users are and what their data requirements are, which will be particularly critical in the next 5-10 years;

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[16] National Digital Twin Program Skills Capability Framework https://www.cdbb.cam.ac.uk/files/010321cdbb_skills_capability_framework_vfinal.pdf [*Accessed April 2021*]

Data stewards and regulators to look after data archiving, in the context of rigorous data management and security frameworks;

Data architects and ontologists to address questions about how data, data producers and data users group into categories, which is critical for understanding how organisations and sectors can work together on the same data;

Data governance specialists to help specifically with creation of policies and standards.

Review of Other Stakeholder Priorities and Opportunities for Collaboration

Ocean observing strategies: the international context

The UK has a strong history of world-leading marine science, and remains one of the top countries globally for oceanographic research. For example, a recent meta-analysis of online databases revealed that whilst the global share in oceanographic (including biology and fisheries) and marine geosciences papers has declined over the last fifty years with the worldwide expansion of scientific publishing, UK researchers are still responsible for approximately 10% of the market share (Mitchell, 2020). Today, the UK plays an important role in global networking and observing strategies, and development of autonomous technology and models.

Collaboration is increasingly key for the efficient use of ships[17], and is likely to play an important role in achieving Net Zero goals. A trend towards enhanced international collaboration is also visible in publication data: over the last fifty years, not only have the number of authors per paper increased in the fields of oceanography and marine geosciences, but also the percentage of UK publications with international partners (predominantly USA, but also strong representation from Germany, France, Australia and Spain). It's essential to place any future recommendation for the steering of UK marine science approaches within an international context, adopting best practice and maintaining the UK's position within the global community and to ensure a coherent and effective strategy that would mesh well with international partners. We will summarise here the identified priorities and directions as documented in the Framework for Ocean Observing (see the Appendix for summaries of other systems, networks, national marine programs, and the International Ocean Discovery Program). Such ocean observing systems, for the most part, focus on strategies for effective and sustainable sustained observations or timeseries, which provide key datasets for monitoring and forecasting, and feedback into critical process-driven or experimental observations (see Science Drivers).

Summary of Framework for Ocean Observing

Systems and Networks

An Ocean Observing *Network* is an ocean sensing system – based on a specific platform, region, or ocean characteristic – that is driven by agreed requirements, has broad scientific support and adheres to global, common standards for data sharing[18]. Examples include Argo and GO-SHIP.

In contrast, an Ocean Observing *System* is a large-scale national, regional or international program founded and funded by governments and stakeholders that builds on networks within a region, with the goal of coordinating observing activities carried out by many partners within the region. The purpose of an observing system depends on societal needs, governmental interests, and scientific interests. Ocean observing networks are members of ocean observing systems[19]. *Such a systems-*

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[17] European Marine Board Policy Brief 7, https://www.marineboard.eu/publication/EMB-publications [*Accessed July 2021*]

[18] A Framework for Ocean Observing. By the Task Team for an Integrated Framework for Sustained Ocean Observing, UNESCO 2012, IOC/INF-1284, doi: 10.5270/OceanObs09-FOO [*Accessed October 2020*]

[19] Optimising and Enhancing the Integrated Atlantic Ocean Observing Systems, https://www.atlantos-h2020.eu/ [*Accessed July 2021*]

based approach allows for discussions to be had on users' needs, requirements, systems design across networks, and technological evolution.

Common themes and approaches: a summary of good practice

The Framework for Ocean Observing (FOO)[20] produced an Integrated Framework for Sustained Ocean Observing in 2012, which summarised a key concepts for designing ocean observing systems (Fig. 12), which has formed a set of principles that have been adopted by many international organisations (see Appendix for examples).

Firstly, the science-driven requirements, resulting from societal issues, must be identified and used to determine the required observations, deployments and maintenance, and the readiness and feasibility of any observational methodologies. The required observations are termed Essential Ocean Variables (EOVs, covering Physics, Biogeochemistry, Biology & Ecosystems, and Cross-Discipline; Fig. 4a [21]) or Essential Climate Variables (ECVs, some relevant physical parameters).

Secondly, it is critical to ensure that the outputs address the issues that drove the original requirements i.e., an evaluation must be carried out that creates a feedback loop for evolving and improving the system (Fig. 4b; Deyoung et al., 2019; Tanhua et al., 2019).

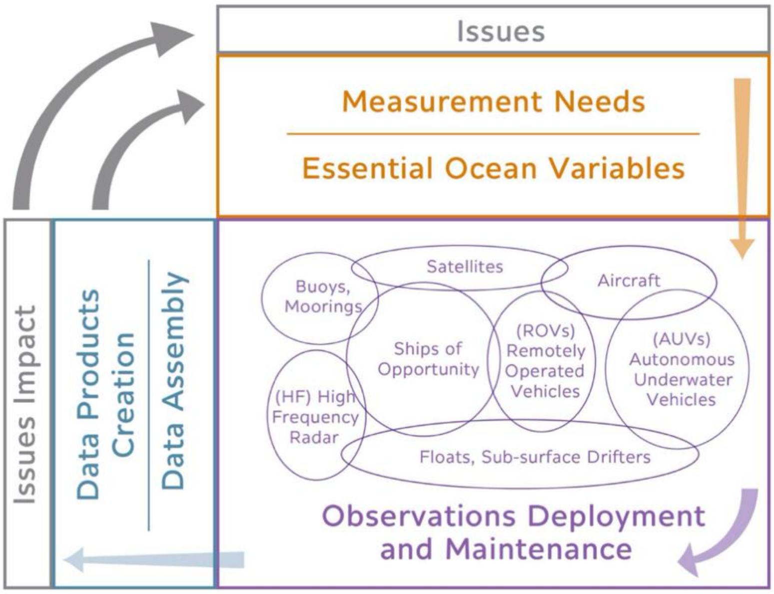

Figure 14: Schematic illustrating the Framework for Ocean Observing, and feedbacks with ocean observing activities, outputs and science-driven needs. From Tanhua et al., 2019.

FOO has had a lot of successes in structuring ocean observing, but also a number of remaining challenges (Tanhua et al., 2019), including the lack of coherent governance; duplication within the system; and changes with data sharing and communication. For example, integration over different spatial scales (i.e., different networks and systems) will likely reduce the number of EOVs/ECVs that can be shared (deYoung et al., 2019).

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[20] A Framework for Ocean Observing. By the Task Team for an Integrated Framework for Sustained Ocean Observing, UNESCO 2012, IOC/INF-1284, doi: 10.5270/OceanObs09-FOO [*Accessed October 2020*]

[21] https://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114 [Accessed May 2021]

Physics	Biogeochemistry	Biology & Ecosystems
Sea state	Oxygen	Phytoplankton biomass/diversity
Ocean surface stress	Nutrients	Zooplankton biomass/diversity
Sea ice	Inorganic carbon	Fish abundance/distribution
Sea surface height	Transient tracers	Marine turtles/birds/mammals abundance/distribution
Sea surface temperature	Particulate matter	Hard coral cover/composition
Subsurface temperature	Nitrous oxide	Seagrass cover/composition
Surface currents	Stable carbon isotopes	Macroalgae canopy cover/composition
Subsurface currents	Dissolved organic carbon	Mangrove cover/composition
Sea surface salinity		Microbe biomass/diversity
Subsurface salinity		Invertebrate abundance/distribution
Ocean surface heat flux		
Cross-Discipline		
Ocean colour	Ocean sound	

Table 4a: EOVs, as defined by GOOS.

Key concepts for an ocean observing system	Key goals for an ocean observing system
Requirement-based science drivers and specific scientific questions Essential (Ocean/ Biological/Climate) variables Improving readiness and feasibility Regular system evaluation Authoritative guidance and effective governance	• Increase both monitoring and understanding of ocean processes • Integrate global ocean and climate observations, including remote sensing, and modelling • Improve essential skills, capabilities and capacities • Improve open information flow from observing system to end-users, including historic data • Improve stakeholder and rights-holder advocacy, interaction and participation • Develop emerging and transformative technologies, ensuring cost-effectiveness • Develop education and training programmes that are fit-for-purpose and equitable • Expand observing systems to include biogeochemical and biological parameters • Encourage multidisciplinary and multi-thematic approaches to ocean observation • Engage with the UN Decade of Ocean Science for Sustainable Development

Table 4b: Common themes relating to key concepts and goals of observing systems that are based on FOO principles.

Global Ocean Observing System

The Global Ocean Observing System (GOOS)[22] was established in 1991, co-sponsored by Intergovernmental Oceanographic Commission of UNESCO, WMO, UN Environment Programme and International Science Council.

GOOS is formed of several groups including: Expert Panels (physics, biogeochemistry, biology & ecosystems) to provide guidance of observing system design; Observations Coordination Group and GOOS Regional alliances that implement the observing strategy; GOOS Projects that focus on innovation; and the GOOS Steering Committee for overall core coordination. The overall GOOS mission is to have a more inclusive governance, and increased expertise, engagement, communication and capacity development, allowing the simplification of project and system design, implementation, data products and evaluation of performance (https://www.goosocean.org/). OceanOps provide technical support globally coordinated observing networks (largely physics and climate) that are members of the GOOS observation coordination group.

The GOOS key vision, enacting the FOO framework, is based on ensuring an effective flow of information from observers to end-users using a responsive observing system (Table 5). Important aims are to: increase monitoring, increase knowledge of oceanic processes; develop new more cost-effective technologies; improve public access to data and information; improve capacity; and increase partnerships and participation.

Deepening engagement and impact	Partnerships Advocacy Knowledge exchange Regular evaluation
Systems integration and delivery	Authoritative guidance Sustain and expand systems Data availability, quality and latency
Building for the future	Innovation Stakeholder participation Expand systematic observations Champion effective governance

Table 5: Main strategic objectives of the Global Ocean Observing System

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[22] The Global Ocean Observing System 2030 Strategy. IOC, Paris, 2019, IOC Brochure 2019-5 (IOC/BRO/2019/5 rev.2), GOOS Report No.239; https://www.goosocean.org/ [*accessed October 2020*]

Policy priorities

Intergovernmental Panel on Climate Change

The intergovernmental Panel on Climate Change (IPCC)[23] is the UN body for assessing the science related to climate change. The IPCC was created to "*provide policymakers with regular scientific assessments on climate change, its implications and potential future risks, as well as to put forward adaptation and mitigation options*". In 2019, the IPCC produced the Special Report on Oceans and Cryosphere in a Changing Climate (SROCC; Pörtner et al., 2019), in essence précising the important findings – agreed by representatives from each country in the UN – surrounding the current state and future predictions for the oceans and icy environments. Whilst not a full assessment, the SROCC highlights the following key issues relating to oceanographic science drivers of particular relevance for policy makers:

- Ice sheet mass loss, and impacts on global sea level
- Changes in sea ice dynamics, and impacts on marine ecosystems
- Teleconnections between polar ocean and atmospheric changes and mid-latitude weather patterns
- Ocean warming and marine heatwaves; ocean acidification and deoxygenation
- Links between tropical cyclones, rainfall, extreme waves – combined with sea level rise – and coastal hazards
- Ecosystem changes associated with cryospheric and hydrological changes, and impacts on ecosystem services
- Changes in species distributions
- Multiple stressors on coastal ecosystems

All IPCC statements are characterised into "(very) high confidence", "medium confidence", and "(very) low confidence" based on an expert evaluation of evidence and agreement. This allows knowledge gaps to be highlighted by the statements that were made with "low confidence", which largely relate to three issues:

- Past climate/pre-instrumental records, including 'data archaeology';
- Transport of heat, carbon, nutrients and oxygen in the modern ocean;
- Models and model parameterisation, and the need for process studies in addition to more data.

In order to conceptualise key knowledge gaps, it is constructive to address the questions: Why can't we be more confident? What is undermining our confidence in these statements? The answers can be divided into two categories:

- Confidence is undermined by *lack of good quality observations*, e.g., oxygen, carbonate parameters, needed to test robust theories (often resulting in medium confidence);
- Confidence is undermined by *lack of good theory*, e.g., biogeochemical fluxes and primary production, limiting how these processes are represented within models (often resulting in low confidence).

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[23] https://www.ipcc.ch/ [*Accessed April 2021*]

UK Government: Marine Science Co-ordination Committee (MSCC)

The Marine Science Co-ordination Committee (MSCC)[24] is a cross-government committee with the aim of coordinating scientific knowledge, resources and communications to support UK government marine policy decisions. The 2021 MSCC report – The Ocean in a Changing Climate[25] – largely draws from the IPCC SROCC, but focuses on priorities most relevant for the UK:

- Impact of sea level rise and storm surges on the UK;
- Other climate impacts on coastal ecosystems e.g., shifts in species distributions, alteration in life cycles, habitat suitability;
- Understanding long-term physical changes in relation to natural variability e.g., wind, wave and storm activity;
- Impacts on coastal infrastructure and industries, including coastal erosion, disease risk, loss of access to coastal spaces, individual and society wellbeing.

The report also emphasises the need to maintain the reputation of the UK world-leading maritime and polar research.

Key MSCC activities within the UK:

- Marine Climate Change Impacts Partnership (MCCIP), with the aim of identifying key challenges and emerging issues of climate change;
- MSCC Social Science Task Group report, on social, cultural and heritage indicators within the marine environment;
- Climate Change Risk Assessment (CCRA) and National Adaptation Plans (NAP) as part of the 2008 UK Climate Change Act;
- UK Climate Projections (UKCP18) with updated projections on e.g., sea level change; Maritime Industries Environmental Risk and Vulnerability Assessment (MINERVA) with projections of broader changes to the marine system;
- North East Atlantic Ocean Acidification Hub, as part of the Global Ocean Acidification Observing Network (GOA-ON);
- G7 Future of the Seas and Oceans Working Group.

Devolved Government Case Study: Scottish Government’s National Marine Plan

In 2015, the Scottish Government[26] released a National Marine Plan[27], reviewed in 2018, outlining the high-level objectives and priorities relating to national marine systems. The report described a number of “good environmental status descriptors” relating to marine health (e.g., biodiversity, non-native species, sustainable exploitation of resources, eutrophication, seafloor integrity, contaminants and marine litter, energy and noise pollution).

The high-level marine objectives were identified as follows:

- Achieve a sustainable marine economy
- Ensuring a strong, healthy and just society

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[24] https://www.gov.uk/government/groups/marine-science-co-ordination-committee; [*Accessed April 2021*]

[25] https://projects.noc.ac.uk/iwg/sites/iwg/files/documents/Ocean_in_a_changing_climate.pdf [*Accessed February 2021*]

[26] https://www.gov.scot/collections/marine-scotland-science/ [*Accessed April 2021*]

[27] Scotland’s National Marine Plan: A Single Framework for Managing Our Seas (2015) https://www.gov.scot/binaries/content/documents/govscot/publications/strategy-plan/2015/03/scotlands-national-marine-plan/documents/00475466-pdf/00475466-pdf/govscot%3Adocument/00475466.pdf [*Accessed April 2021*]

- Living within environmental limits
- Promoting good governance
- Using sound science responsibly (using the precautionary principle)

The report also included sections fully dedicated to marine resources and related marine planning policies, highlighting the main policy priorities, with a particular emphasis on sustainable development, coastal change and flooding, marine protection, and invasive non-native species, water (and air) quality and pollution, cumulative impacts, fairness and engagement.

The policy priorities included sea fisheries (specifically including wild salmon), aquaculture, oil and gas, carbon capture and storage, renewable energy, tourism, shipping, submarine cables, defence, and aggregates.

Other UK marine science organisations: the journey towards Net Zero

Marine science organisations around the UK, not linked directly with NERC or NMF are also undergoing transitions to Net Zero. Identifying the challenges that are faced by these organisations, is a useful exercise to determine commonalities and find potential opportunities for cooperation and efficiency savings.

Case Study 1: Plymouth Marine Laboratories

The Plymouth Marine Laboratory (PML) operate two vessels: the *RV Plymouth Quest* and a rigid inflatable boat with twin outboard motors. PML have started to plan the replacement for the *RV Plymouth Quest*. The technology required to operate a Net Zero replacement is considered over five years away, and so other strategies are being investigated:

- Use of hybrid engines;
- Designed with options to retrofit future clean fuel technologies;
- Reducing carbon footprint in other ways (travel processes, especially international travel; increase in remote meetings (where appropriate); increase in energy savings e.g., with heating system; use of renewables e.g., electric car charging points on site);
- Careful planning to meet science needs; better communication between disciplines for increased efficiency; use of smart sampling;
- Better planning of data infrastructure.

Case Study 2: Scottish Association of Marine Science

One of the Key Performance Indicators for the Scottish Association of Marine Science (SAMS) surrounds environmental sustainability. Principal objectives include implementation of its carbon management plan; reduction of greenhouse gas emissions; and implementation of a robust waste hierarchy. SAMS has a Sustainability Group – currently led by postdoctoral researcher, Kristin Burmeister – which is pivotal to realising these objectives. SAMS management team and the Sustainability Group are working on several activities to do this and therefore improve the environmental impact of the organisation. Initiatives include implementing projects that will use renewable energy; replacing key infrastructure with more sustainable equivalents, targeting resource-intensive laboratories; reduced use of plastic; and improving communication and collaboration internally, throughout Scotland and across the rest of the UK (e.g., via Marine Alliance for Science and Technology for Scotland - MASTS). Through the Transport part of the Sustainability group, Saz Reed is leading the decommissioning of the SAMS' main vessel, *RV Calanus*: sustainability is at the heart of plans for its replacement, although many technological developments (e.g., engine design) are not yet available. Sustainability will also drive the replacement of SAMS' smaller vessel, *RV Seol Mara*, when that is due. Meanwhile, SAMS will also be developing a vessel management plan to improve efficiency of its seagoing activities by forming stronger links between user activities, to improve sharing of resources and equipment, and to use third party vessels more effectively over the lifetime of projects.

Collaborations outside of academia and policy-making: linking up with the private sector

There is a significant appetite within non-academic and private sector organisations (technologies, defence, citizen science) to work with scientific researchers in utilising ocean technology, and taking advantage of different approaches to carrying out and communicating ocean observations (NZOC Industry Workshop). However, there is still a need for more effect dialogues between scientists and private sector organisations in order to take full advantage of the opportunities for collaboration, and boost the field of ocean observation through testing technologies, improving data readiness, standardisation and networking (i.e., collecting the right data, setting standards for data, and sharing data securely).

What are the barriers to effective collaborations between academia and the private sector?

1) **There is technology that is not being used to its full potential**, such as onboard processing of data for transmission to land-based data centres; launch and recovery capability of AUVs from research ships; transmission of data through water; standardisation of research data, for example by Nekton through the GOSSIP[28] project; digital twins, which are already being developed, for example by the National Digital Twin program[29], Ocean Data Platform[30], and Microsoft; Earth Observation Satellites[31], and intermediaries that deal with remote sensing data management, such as Ocean Mind[32]. Barrier to partnerships between academia and these organisations to develop technology is potentially due to communication and networking opportunities or funding availability.
2) **There are possible partnerships that are not yet realised**, including international partnerships, links between sectors, marine monitoring programs (such as organisation involved in forming and monitoring Marine Protected Areas), and multi-use areas (e.g., wind farms, aquaculture etc.). Often the barrier to partnerships between academia and these organisations is a matter of communication and networking opportunities.
3) **Such partnerships may be inherently challenging.** A key challenge is that all data for oceanographic research needs to operate under the FAIR principles (findability-accessibility-interoperability-reusability). Data accessibility for scientists could be restricted, especially from defence or commercially sensitive platforms, where the data has inherent monetary value. When data are available, integration and inter-operability between sectors is often challenging, and there is a need for effective exchange of data between systems and sectors. Data storage and infrastructure/architecture issues need to be addressed: a common systems-based approach across sectors is essential for efficiency savings.

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[28] https://nektonmission.org/science/gossip [*Accessed April 2021*]
[29] https://www.cdbb.cam.ac.uk/what-we-do/national-digital-twin-programme [*Accessed May 2021*]
[30] https://www.oceandata.earth/ [*Accessed April 2021*]
[31] https://www.planet.com/ [*Accessed April 2021*]
[32] https://www.oceanmind.global/ [*Accessed April 2021*]

Proposed Roadmap

Long-term Vision

We propose a roadmap for future marine technological developments that takes full advantage of emerging technologies in the fields of automation and artificial intelligence. It is, however, important to recognise that gaps could arise in UK marine science capability if the future research fleet is limited to fully-autonomous platforms. **A hybrid system of "autonomy where possible" coupled with the continued operation of multi-purpose crewed research vessels, which can be made more efficient through improved co-ordination and data flow, would allow the UK to maintain their position as a world-leader in sea-going science and technology whilst also meeting Net Zero targets.**

The roadmap (Fig. 16) illustrates the possible evolution of different marine science measurement strategies. It reflects to some extent the current perspective of the marine science community towards automated sampling (i.e., trust in the technology). The pace of progression through the roadmap will depend on multiple factors—certainly on the pace of technological development, but also on the rate at which trust in the methods is built by and within the scientific community. Many of the traditional measurement methods have been established over decades or longer, during which time they are continually subjected to scrutiny, re-evaluated, and reprocessed when new information comes to light (e.g., grey listed Argo floats with faulty pressure sensors, XBT fall rate adjustments when manufacturers changed).

Current rate-limiting steps towards progression through the roadmap include:

- Insufficient 'proof-of-concept' for new sensor technology. The acceptance of new methods in the scientific community requires demonstration activities and publication of 'proof-of-concept' papers. The proof-of-concept for the sensor may then only be valid for the environmental conditions, sampling strategy and endurance used in the demonstration activity. The accuracy, precision and stability of the measurement need to be established in order for the sensor to be used more widely. This step is required to increase trust in the technology, and therefore to increase its value to the scientific community. Once a method is established in this way (possibly by multiple institutions/multiple demonstrations), then more widespread use can be anticipated.
- Time investment by scientists to learn to use new technology, where this time investment will not necessarily be proportional to scientific outputs. Using autonomous platforms requires time investment by the PI and team – to learn how to request autonomous platforms, how to use them for the scientific purpose of the project (even if not requiring the scientists to learn how to interact with the hardware), and how to handle the data coming off of them. The use of e.g., new platforms with reduced reliability (compared to research vessels) may put the scientific outputs in jeopardy, unless they are used in parallel with traditional methods – which further increases the time investment required.

In addition to the rate-limiting steps, there are a number of critical risks to investment in new technology.

- Accuracy and precision. Some scientific applications require a very accurate measurement to resolve small signals. For some communities (e.g., hydrographic measurements) these requirements have been established by international ocean observing strategies (e.g., GO-SHIP) and provide useful targets for the technology developments.

- Stability of sensors. Given the long endurance of autonomous platforms (gliders up to 1 year, Argo floats for 3-5 years), not only must the accuracy of sensor technology be established, but its stability as well – i.e., does the sensor drift with time? If the stability cannot be established, then the measurement quality is at risk (is the sensor drifting or is the ocean warming?) or the long endurance capability of the platform cannot be fully maximised.

Developments in both sensors and platforms that may be achievable within different timeframes are associated with the different disciplines in the shaded boxes, illustrating that many of the emerging technologies will serve multidisciplinary activities. Developments in sensor technology for some parameters are well underway, but will require continued improvements and wider usage in the next 5-10 years to achieve acceptance by the marine science community (temperature, salinity, oxygen, nutrients, carbonate parameters, bio-optics). The target accuracies for these parameters are well-known and have been defined by international ocean observing strategies. Developments in platform technology are likely to see rapid changes in the same timeframe (e.g., automated ships, deep-sea and under ice platforms), but the outcome of these developments and their ramifications for marine science are less well known.

Some sensors are in very early development and are unlikely to be used widely this decade (eDNA, metabolites and other 'omics', pollutants). Some developments for the broader use of autonomous platforms (e.g., glider swarms, fully remote AUVs with fully automated sampling equipment) require step-changes in order to be effective, both in the approaches to oceanographic observing (e.g., implementation of hydrographic sections) and/or information technology (telemetry, bandwidth, artificial intelligence, model integration and oceanic 'digital twins'). These can be considered the "stretch targets" for the next two decades. Lastly, there are important marine science applications where fully automated sampling is unlikely to be achievable by the middle of the century, including aspects of experimental observations, benthic habitat mapping, sediment and rock coring.

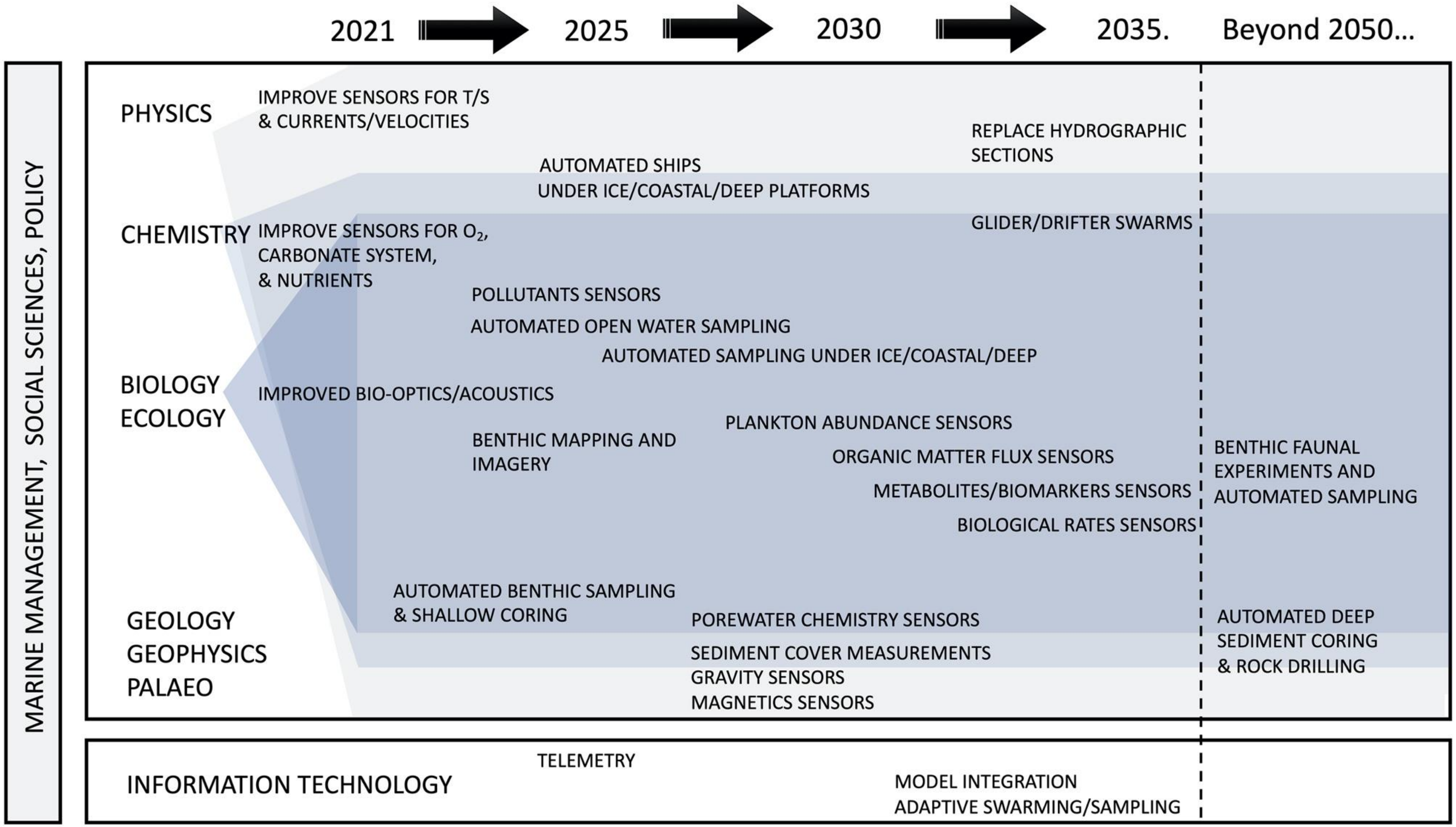

Figure 15: Swim lanes analysis of future requirements for UK marine science

Improving efficiency

It is highly likely that, within the Net Zero timeframe, there will remain some activities that can only be carried out on a ship. To improve efficiency and value for money, we need to coordinate usage and do "*more from the ships when the ship is doing things that only ships can do*". This could be achieved by combining and interconnecting the different, new technologies, for example through deployment of smart and adaptable autonomous vehicles (aerial, surface, marine, submarine, subsurface) and sensors, with deployment planned using coupled models or "digital twins" and AI. We also need to widen access to the ships, which could be supported by changes to current funding structures (e.g., smaller "add-on" grants to carry out complementary research on an existing cruise). There is scope for using research vessels for continuous underway measurements between process study locations, further increasing the science benefit per unit cost of the carbon expenditure[33].

There is also potential to improve efficiency through changes to resource scheduling, for example through the expanded use of facility and equipment pooling, and boosted use of international ship barter systems. Given that coastal/shelf research is only approximately 10% of current published marine research (Brannigan, 2021), there is likely to be a continued demand for open ocean expeditions; enhanced international collaboration, effectively establishing regional research "hubs" that can be used by any nation, would reduce the travel distance required. Such collaboration would require significant engagement on an international scale, and may take many years to establish.

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[33] EMB Policy Brief 9, https://www.marineboard.eu/publications/sustaining-situ-ocean-observations-age-digital-ocean [*Accessed July 2021*]

Key Challenges – Risk Management and Transition

One potential risk in the strategy of "automation where possible" would be a lack of trust in autonomous observations within the science community. The WP1 horizon scan indicates that quality control is one of the main barriers to the current use of autonomous technologies for measuring EOVs. A additional but related risk is that a lot of energy, time, and money is put into automation, but then **gaps develop that limit UK marine science capability**. These risks can be managed through flexibility: support research and development to automate where possible within and between disciplines, but also put resources into making the current system more efficient in terms of fuel sources and usage, sample and data co-ordination, and use of plastics.

Furthermore, many of the risks associated with community uptake of emerging technologies can be mitigated **through co-design of Net Zero solutions between scientists and technology developers**. It will be essential to plan pilot studies early, before their rollout and throughout deployment, and embed scientists and data experts within the planning process, with continual quality control and feedback[34].

Discipline-specific case studies

Here, we illustrate some possible, flexible 'hybrid' futures for different scientific disciplines, before presenting a matrix of general risks associated with each future. We recommend that the transition planning account for specific use cases in order to evaluate (on paper) what the effect of a transition to Net Zero would mean for that activity.

Large-scale ocean circulation variability: RAPID 26°N

Monitoring the strength of the large-scale ocean circulation, including the Atlantic meridional overturning circulation, requires high accuracy and high frequency measurement of temperature, salinity and pressure.

The method used by transport mooring arrays such as RAPID 26°N, OSNAP and SAMBA 34.5°S relies on boundary measurements of vertical profiles of ocean density, computed from *in situ* measurements of temperature, salinity and depth (CTD). At present, these measurements are made using moored observations, where a large ship is required to go to the site, recover a ~5km tall mooring, carry out calibration activities, and re-install a tall mooring with self-logging CTDs. The CTDs on the moorings are set to sample hourly, in order to de-alias the tides (~12 hour frequency). Moored CTDs are checked against the ship-based high-accuracy CTD by attaching them to the CTD rosette and lowering them to prescribed depths for 'bottle stops' where the moored CTDs and ship-based CTD are both sampling. The ship-based CTD (Seabird 911plus) is then evaluated against seawater samples collected at those depths and measured in the on-board laboratory against international standards, while the temperature measurement is checked against an ultra-stable thermistor (Seabird 38).

Carbon cost (as ship-days): The moored approach allows high quality data to be recovered hourly for a timespan of 18-months to 2 years, and because measurements are made at ocean boundaries (in the case of RAPID 26°N and SAMBA 34.5°S) only require short-duration research cruises to the site. For RAPID 26°N, this involves a 9-day cruise to and from the Canary Islands every 2 years, and a 7-day cruise to and from the Bahamas every 2 years.

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[34] See Tropical Pacific Observing System (TPOS) recommendations, 2nd Report of TPOS 2020, https://tpos2020.org/project-reports/ [*Accessed July 2021*]

Observational challenge: The particular challenge of these measurements is to ensure high accuracy and to eliminate interference by high-frequency (tidal) variability. The moored CTDs have a stated temperature initial accuracy/stability/resolution of 0.002°C, 0.00002°C/month and 0.0001°C, while the conductivity is 0.003mS/cm, 0.003 mS/cm/month, and 0.0001 mS/cm. This accuracy is important as a 0.003 difference in salinity leads to a 0.7 Sv error (1 Sv = 1,000,000 m3/s) in the estimated ocean transport (McCarthy et al., 2015), where the mean transport is about 18 Sv and fluctuations include a measured tendency of 0.5 Sv/year. This is a small change compared to the observational error, but a large change in that it exceeds the change predicted by climate models (Smeed et al., 2014). Additionally, hourly sampling ensures that the highly sensitive measurement is not aliased by tidal fluctuations which are common near ocean boundaries.

Reduced carbon approaches: Based on the 16-year record from RAPID (2004-2020), the largest signals of variability are derived from the western boundary moorings offshore of the Bahamas. In this region, there are strong currents (1 knot) both near the surface and in the deep western boundary current, and active tides. Additionally, important signals of interannual and decadal change are present in the deep (below 1500m) watermasses. Due to the proximity to shore (1 day from major ports in Florida, or hours from Nassau or Freeport, Bahamas), the shiptime required to carry out servicing of these moorings is relatively small compared to the value of the data returned (+4 days added to a cruise shared with US partners at NOAA and University of Miami, and requiring only 6 personnel to travel from the UK to join the ship. The moorings provide reliable and highly accurate measurements necessary to de-alias tides and measure small signals of change. In the east, however, the signals of change are primarily on seasonal timescales, contribute less to the transport variability and are confined to the top 3000m. It may be feasible to consider alternate, autonomy-based approaches to measure the eastern boundary contribution to the large-scale ocean circulation variability. Additionally, efforts are underway to use multiple observational constraints, based on satellite altimetry, Argo profiling floats and repeat hydrography to estimate ocean transports in near real-time and without dedicated in situ observations. At present, these estimates of transport variability are benchmarked against the RAPID time series, and have been found to capture the variability of the transport well (i.e., correlations between the altimetry+hydrography approach are high) but the magnitude is too large by a factor of two. This is thought to be due to incompatible spatial sampling of the profiling floats compared to nadir-looking altimeters, and may be remedied once the SWOT altimeter is launched (Calafat et al., in prep).

Biogeochemical fluxes

The study of biogeochemical cycles in involves the assessment of stocks and fluxes of key nutrients, which could be in both bioavailable dissolved forms or reactive particles. It is essential to establish not only the concentration of these nutrients but their form (truly dissolved, complexed, colloidal, particulate) and reactivity, in addition to the rates of change in the system, through dissolution, flocculation, sinking and upwelling.

Currently, dissolved nutrients concentrations including carbonate parameters (dissolved inorganic carbon, pH, alkalinity), inorganic macronutrients (e.g., nitrate, nitrite, ammonium, silicic acid and phosphate), inorganic micronutrients (e.g., iron, cadmium, zinc, cobalt), and organic nutrients are assessed by the collection of samples using Niskin bottles (or equivalent) often attached to CTD rosette frames. These collection bottle systems have not changed in design for decades with the exception of the introduction of trace-metal clean options. Analysis is then carried out using shipboard equipment or preservation at sea for land-based analyses. Work is in development in the emerging fields of autonomous macronutrient analysis using sensors or lab-on-chip technology on moorings and AUVs.

Particle and colloidal material is collected using similar Niskin bottles, followed by filtration and, usually, preservation at sea for land-based analyses. Large volumes of seawater can be filtered at high rates using ship-deployed Stand Alone Pumps (SAPs). Emerging technologies for autonomous particle analysis include the use of video equipment and bio-optics sensors on AUVs. Particle sinking fluxes are classically assessed using sediment traps moored at different depths in the water column, and more recently with the addition of ship-deployed Marine Snow Catchers (MSCs), now also available in trace-metal clean versions, which can provide additional information about sinking and suspended particulates.

Other biogeochemical rates can be assessed using stable and radioisotope geochemistry, requiring ship-deployed collection of often large volume samples. Many isotope systems are limited to land-based analyses given the large analytical equipment required, carrier gases, reagents and power supplies, and the need for physical stability. Process-based studies are also carried out using shipboard incubations and experiments (e.g., dye or isotope-labelled uptake experiments or sediment core incubations), followed by a combination of shipboard or land-based analyses.

Whilst a significant proportion of biogeochemical work can be carried out autonomously either now or in the timeframe of the next two decades, this work is generally associated with *sustained observations*. For example, there is a good likelihood that there will be development in the field of nutrient sensors and lab-on-chip technologies allowing for many nutrients to be measured routinely using autonomous platforms, which would be a critical development for timeseries and high-resolution spatial mapping. However, there are potential limitations in autonomous measurement of some target variables, such as complex organic compounds and low-level ‘ultratrace’ metals, which will still require the collection of physical samples. Small samples could be collected remotely using AUVs where possible, provided that essential filtration or other preservation methods can be carried out.

Significant challenges associated with *experimental observations* involve particulate sinking and dissolution reactions, rates and fluxes. Some autonomous solutions for these process-based studies could be possible, but there are some geochemical analyses that will *not be possible at sea* because they require very large analytical equipment (e.g., Accelerator Mass Spectrometer, or synchrotron analysis of particles). Our recommendation is that a hybrid solution of autonomous observations where possible, coupled with targeted ship-based sampling, would lower the risk of losing critical capabilities in experimental marine biogeochemistry.

Dissolved organic and inorganic nutrients mostly measured using sensors/lab-on-chip, and/or autonomous sampling, coupled with some targeted ship-based sample collection for calibration and quality control, to account for risks associated with sensor drift, biofouling, reagent depletion, sample degradation etc., and allowing the rapid retrieval of samples. Similarly, autonomous collection/filtration of particles, and full use of autonomous photography and bio-optics using AUVs, could be coupled with targeted ship-based sampling (e.g., using SAPs) and sediment trap moorings. Particle analyses from bio-optics sensors fitted to floats and gliders could provide high-resolution mapping of particle sinking and size in space and time, ultimately integrated into digital twin models of the ocean. Stable and radioisotope geochemistry could be carried out by automated sample collection or ship-based sampling where needed, incorporating preconcentration methods to reduce the volume of water being transported. Shipboard incubations and experiments could be carried out on smaller, specialised vessel; using ship-based

experiments rather than autonomous method would reduce risk of environmental contamination when dealing with radioactive isotopes or toxic chemicals.
Ship-based or autonomous platform-based analyses would increase efficiency of data acquisition, and reduce the carbon cost of transporting samples, but would come with an additional carbon budget relating to the production of reagents (especially organic solvents), transportation of gases, and the power requirements for the analytical equipment.

Benthic ecology and habitat mapping

Loss of biodiversity is one of the key future challenges. The seafloor is home to significant biodiversity, and provides important ecosystems services including fish nurseries, control of water quality, and natural products including pharmaceuticals. The benthic environment is also high sensitive to physical disturbance, including trawling, in addition to changes in seawater oxygen and pollution. Assessing benthic habitats, and the controls on population distributions, is essential for predicting future declines or recoveries in seafloor ecosystems.

Benthic ecology and habitat mapping is currently carried out semi-autonomously, using towed camera systems or remotely operated vehicles (ROVs) tethered to a ship. Images (high-definition video and photographic stills) are used to investigate the distribution of benthic organisms. Trawls, dredges and box-cores are used where access to an ROV (or a towed-camera system) is not possible. ROV-based photogrammetry or high-resolution multibeam can be used to map the seafloor and assess seafloor properties, often supplemented with sediment cores. However, this semi-autonomous approach is always coupled with sample collection, for example using manipulator arms or suction systems attached to the ROV, because benthic organisms (especially invertebrates) can be challenging to identify to genus or species level by using images alone. Physical samples are required for taxonomic and genetic identification, and must be recovered, triaged and preserved rapidly, by different means for different types of analysis, before decay can occur.

A good proportion of the work involved in benthic ecology and habitat mapping can continue to be done (semi-)autonomously in the future. More acoustics and multibeam can be carried out fully independently of a research ship, including sound velocity profiles (SVPs), and CTDs. There could also be an expansion in the use of photogrammetry and imaging remotely from AUVs. Sensors for organic compounds, such as eDNA and ‘omics’ technology could be developed to provide a certain amount of information about which organisms are in the environment and carrying out which biological processes. Note that bacteria and viruses are particularly challenging to detect via eDNA, and involves large volume sampling. However, there will *always be a need to collect physical samples of benthic life for specific identification purposes*, to ground-truth sensors, and for natural resource research (e.g., pharmaceutical applications). These samples will need rapid preservation, posing a significant engineering challenge if this is to be done entirely autonomously. An AUV (potentially using hover technology) could potentially sample specimens, controlled by pilots and scientists back on land, but the telemetry, bandwidth, and power supply required for the high-definition video feed and high-precision instrument control would be considerable. Data throughput would be high, requiring the development of artificial intelligence approaches to prevent a processing “bottle-neck”. Whole samples, or at least relatively large portions of a specimen, are required for taxonomic research, resulting in a large payload for an AUV collection. Sediment cores pose their own challenges relating to autonomous collection.

The risks of limiting the UK’s capacity for carrying out benthic research would be reduced by opting for a hybrid solution, improving efficiency by using different technologies for different applications. Sparsely populated, low-diversity regions (e.g., abyssal plains) could be rapidly mapped over a wider geographic area using fully-autonomous systems with limited sampling capacity. More diversity-rich, heavily populated regions (e.g., continental shelves, seamounts) could be initially surveyed using full-autonomous technology, and then targeted using semi-autonomous ship-based, advanced fleet of ROVs with greater sampling capability.

Marine geology and rock drilling

Marine geology is an important of area of research, providing key information required for understanding Earth's climate in the past and, so, climate sensitivity and feedbacks in the Earth system (i.e., palaeoceanography); Plate tectonics and Earth history; Marine geological hazards (e.g., tsunamis); Extreme life and the origins of life; and Global cycles of energy and matter.

Currently, the majoring of deep-sea drilling for research purposes is carried out by the International Discovery Program. Site surveys are initially carried out to collect seismic data on the subsurface properties of the seafloor. There is no central IODP funding for site surveys, and - for UK researchers - this stage in the program is carried out in co-ordination with UK-IODP, utilising tendered vessels capable of seismic surveys in addition to the national fleet.

One the sites are selected, deep sediment and hard rock cores are collected in 10m sections, up to 1.5 kilometres in total length, in sometimes several kilometres water depth, often requiring more than one expedition. Several kilometres of drill pipe are needed in total. Specialised ships (e.g., the R/V *Joides Resolution*) initially deploy a re-entry cone to the seafloor equipped with cameras, before deploying the drill pipe. Smaller seafloor drills (e.g., those owned by the British Geological Survey) are used in UK research ships and EU platform-specific expeditions, and can drill down 60-100m, bringing up a "cassette' of cores. Whilst there is some potentially for these smaller operations to be automated, *the extremely heavy payload associated with the larger drilling programmes is likely to be prohibitive for automation at least within the next generation or two*.

However, IODP have some strategic plans for increasing the efficiency of the operations. The initial site surveys, using seismic technology, could be automated. There could also be a greater use made of existing "legacy holes" that have re-entry cones. Sensors, arranged in "corks" could be used in legacy holes to assess fluid pressure, temperature, microbiology and fluid sampling, and other parameters critical for long-term monitoring of hydrothermal processes. Multidisciplinary, slimline "cork light" systems could be developed that do not need drill ships. Such sensor technologies are emerging, and are likely to be operational in the timescale of approximately five years, although some sensors required for the monitoring of hazards may require a greater degree of sensitivity and so may emerge over a longer timescale. Artificial intelligence technology could be used to obtain more data more quickly from samples, including score scanning and logging approaches. Furthermore, improved networking technologies – planned by IODP over the next 15-20 years - could allow for better communication and better planning, making expeditions more efficient. Lastly, better environmental credentials could be achieved through the choices made when tendering vessels – such as ships powered by carbon-free or hybrid technologies - for site surveys and lighter payload work.

Impact of Different Net Zero Strategies

Vision	Advantages	Opportunities	Challenges	Risks
"Business as usual" **Use of large, multidisciplinary ships in UK fleet**	All current scientific areas of research continue to be served by UK fleet No additional skills training required	Use of multidisciplinary ship could encourage integration of research topics, themes, disciplines. With other fleet managers looking to reduce carbon, there are opportunities to optimise vessel use across fleets.	Net-Zero attainment without *significant* carbon capture and storage, or other offsetting technologies Efficient integration of emerging technologies	Net-Zero not obtained by 2035 Lack of flexibility UK reputation as world-leader in marine research diminishes without the integration of emerging technologies
"Hybrid model" **Use of partially automated fleet to carry out aspects of science achievable using emerging technologies (largely sustained observations); efficient use of smaller crewed vessels to target specific scientific challenges (largely experimental observations)**	All current scientific areas of research continue to be served by UK fleet Net-Zero *achievable* through various options for efficiency savings and offsetting e.g., hybrid engines, digital twins, 'smart' sampling Inbuilt flexibility	Continuation of UK as world-leader in cutting-edge marine technology More efficient use of data by stakeholders Broadening of access (and recruitment) to marine sciences Broadening of skills training	Encouragement of cross- or multidiscipline research, as specific platforms for research themes evolve Encouragement of participation/recruitment of scientists without sea-going expeditions *in some research themes* *Change* within skills training	Potential loss of multidisciplinarity without *significant* push towards collaboration and coordination
"Fully autonomous" **Use of fully automated fleet**	Sustained observations and *limited* experimental observations served by UK fleet Net-Zero *readily achievable* with minimal offsetting	Continuation of UK as world-leader in cutting-edge marine technology More efficient use of data by stakeholders Broadening of access to marine sciences	Encouragement of cross- or multidiscipline research, as specific platforms for research themes evolve Encouragement of participation/recruitment of scientists without sea-going expeditions *in all research themes* *Change* within skills training	Some aspects of marine science not achievable (e.g., biogeochemical process studies, benthic sampling, marine geology, palaeoceanography) Loss of multidisciplinarity Reduced recruitment of ECRs Loss of skill sets Lack of flexibility

Key recommendations for achieving roadmap: Input and output analysis

For alignment of recommendations with UKRI/NERC policy, see Appendix 5.

	Strategic oversight	
INPUT	**RECOMMENDATION**	**OUTPUT**
Community engagement	**Form a working group to identify priority development areas for marine science observing over the next five years**, to outline requirements (e.g., sensor accuracy, positional accuracy, depth-rating) and the user group / science outputs that would be supported by this development. **Specifically, undertake an additional analysis of the marine science community sensing requirements.** For specific applications (currently undertaken by the marine science community), what are the sensing requirements including accuracy, precision, stability, sampling interval and endurance of the sensor. This would provide a more complete set of 'user requirements' for the engineers involved in platform and sensor development. **Maintain regular contact with the science community to carryout horizon scans of key science questions and drivers**, in dialogue with policy experts, with assessment every 5-10 years. **Keep flexibility within the funding system from the start to allow for the unknowns.**	UK marine science resourcing strategies that are fit for purpose to address science drivers into the future
	Co-design between technologists and scientists	

INPUT	RECOMMENDATION	OUTPUT
Resourcing strategy International strategy Improved data ecosystem Evolved fit-to-purpose view of marine science careers with expanded specialisms, including data and technology experts	**Maintain a dialogue over the next five years between scientists and technology developers regarding the platform and sensor requirements needed for the effective delivery of key science goals.** Introduce funding calls across Research Councils (in particular NERC, EPSRC but also ESRC and MRC) over the next five years to promote such collaboration to improve on existing technology and develop new emerging technologies. Consider scoring existing grant calls in order to encourage collaboration between scientists and engineers to develop new ways of carrying out (existing or novel) research autonomously. It is not recommended to reduce the capacity of the UK marine science fleet until the replacement technology (platforms and sensors) are 'trusted' by the marine science community. While it might be possible to gauge trust through surveys, this is a subjective exercise. Alternative methods to gauge trust include (i) tracking the publication of papers that provide the necessary 'proof-of-concept' of a sensor or platform, and (ii) recommending that sensors undergo the trials and acceptance procedure for established international ocean observing programmes, e.g., BGC Argo.	Reliable platforms for long duration Reliable platforms for challenging environments (polar, deep, ice) Improved physical sensors Improved and new chemical/biogeochemical sensors New biological sensors New and improved geological sensors
Reliable platforms for long duration Reliable platforms for challenging environments (polar, deep, ice)	**Invest in discipline-specific requirements across the marine sciences.** Support the roll out discipline-specific developments and broadening of access.	
Improved physical sensors	**Physics:** Invest in building multiple observational approaches, including satellite altimetry, Argo profiling floats and repeat	New ways of carrying out hydrographic sections and other sustained observations

	hydrography using autonomous technology, over the next 10-20 years.	
Improved and new chemical/biogeochemical sensors	**Chemistry/biogeochemistry:** Invest in sample collection methods, including preconcentration methods, to allow for autonomous collection of large volume water samples, over the next five years.	New methods for sampling remotely and/or using low carbon ship options
	Invest in autonomous means for assessing particle fluxes, over the next 5-10 years.	
	Allow for the continued use of ship-board experiments and incubation studies i.e., experimental observations, to avoid risk of limiting critical biogeochemical research. Investment in autonomous means to carry out experiments from 10-20 years.	New methods for carrying out experimental observations remotely and/or using low carbon ship options
New biological sensors	**Biology/ecology:** Invest in improved midwater acoustic technology.	New methods for carrying out midwater and benthic habitat surveys remotely and/or using low carbon ship options
	Invest in ROVs to reduce the use of trawls and dredges over the next five years, and expand the use of long-range AUVs and photographic systems over 6-10 years.	
	Investment in research and development into the emerging technologies of eDNA and ‘omics’ sensors and remote sampling of small benthic biological and sedimentological samples (10-20 years timescale). Maintain flexibility for continued and more efficient use of semi-autonomous ship-based work.	
New and improved geological sensors	**Geology/geophysics:** Establish funding opportunities (potentially joint with IODP) for use of “legacy” IODP holes from the start.	New methods for carrying out sediment coring remotely and/or using low carbon ship options Strong international partnerships for rock drilling, to carry out essential research whilst minimising GHG emissions

	Develop multidisciplinary, slimline “cork light” systems for reoccupation of “legacy” IODP holes over next five years. Develop automated or low carbon site survey technology over 5-10 years. Establish funding opportunities for IODP initial site surveys, using automated or low carbon seismics technology over 10-20 years. Support IODP networking technologies over the next 15-20 years.	
Community engagement	**Invest in an equitable, diverse and inclusive marine science community.** Establish a practice of monitoring equality, diversity and inclusion as the path towards net zero is undertaken, to evaluate what expected and unforeseen consequences may be occurring as technology-based decisions are made. Decide in the next 1-2 years on an approach to - and who has responsibility for - monitoring EDI in the evolving marine science community. Over the next five years, expand resources for EDI training and recruitment of underrepresented groups, through enhanced visibility, outreach, and mentoring. Engagement with community organisations (Challenger Society, Marine Biological Association, Geological Society) and EDI special interest groups (e.g., Diversity in UK Polar Science Initiative).	A fair, equitable and diverse UK marine science community Effective EDI monitoring
Resourcing strategy Improved data ecosystem Improved data availability Improved data quality control	**Encourage continued interaction between observational and modelling marine researchers.** Introduce funding calls across Research Councils (in particular NERC, EPSRC but also ESRC and MRC) over the next five years to promote such collaboration. Encourage collaboration between scientists and modellers to develop new ways of improving existing models and devising new approaches.	The next generation of UK ocean models

Improved processing power		
	Milestones to measure progress	
INPUT	**RECOMMENDATION**	**OUTPUT**
Progress reports and publications from development efforts	**Milestones to measure progress.** The development process is not linear and the complexity of marine fieldwork to trial methods adds uncertainty. A set of milestones must be developed (e.g., ‘proven sensor accuracy’ or ‘pilot study results accepted by the international community’) to evaluate whether progress towards Net Zero is on track, and if not then the transition timing and its feasibility must be re-evaluated.	Decisions on whether to continue development or redirect investment
	Workforce training	
INPUT	**RECOMMENDATION**	**OUTPUT**
Resourcing strategy A fair, equitable and diverse UK marine science community	**Develop data skills training programmes for all marine scientists.** Over the next 1-2 years, hold workshop to bring together UKRI (across all Research Councils), Higher Education Institutes, and the private sector to align data training requirements. **Invest from now in training targeted at early career scientists** to learn (i) to use large datasets and (ii) to use autonomous platforms. This subset of the scientific community is most likely to take advantage of new measurement methods over their career. Investment in programmes such as the NEXUSS CDT or Advanced Training Short Courses can speed the transition towards wider use of autonomous platforms.	Evolved fit-to-purpose view of marine science careers with expanded specialisms, including data and technology experts

	Ensure that there the sufficient trained specialists in place for an effective future data ecosystem from the start. Fund new training and recruitment over the next five years. Assess after five years how the needs for data science training and recruitment are progressing.	
	Invest in an equitable, diverse and inclusive marine science community	
INPUT	**RECOMMENDATION**	**OUTPUT**
Community engagement	1. **Invest in an equitable, diverse and inclusive marine science community.** Establish a practice of monitoring equality, diversity and inclusion as the path towards net zero is undertaken, to evaluate what expected and unforeseen consequences may be occurring as technology-based decisions are made. Decide in the next 1-2 years on an approach to - and who has responsibility for - monitoring EDI in the evolving marine science community. Over the next five years, expand resources for EDI training and recruitment of underrepresented groups, through enhanced visibility, outreach, and mentoring. Engagement with community organisations (Challenger Society, Marine Biological Association, Geological Society) and EDI special interest groups (e.g., Diversity in UK Polar Science Initiative).	A fair, equitable and diverse UK marine science community Effective EDI monitoring

	Work with Industry	
INPUT	**RECOMMENDATION**	**OUTPUT**
Resourcing strategy International strategy Improved data ecosystem A fair, equitable and diverse UK marine science community	**Work with industry and other private sector partners to take advantage of technology already under development and open up new opportunities**. Expand UKRI (cross Research Council) opportunities (including seedcorn funding) over the next five years, targeted at linking up private sector and academic research, including citizen science, to use technology to full potential and form new partnerships. Reassess after five years the progress of stakeholder engagement to identify any continuing barriers to collaboration.	Effective partnerships between scientists and private sector organisations
	Work with other scientific organisations within and around the UK, including devolved governments, to ensure integration of approaches and efficiency in the journey towards a Net Zero future. Carry out targeted stakeholder workshops over next 1-2 years, in particular to derive a roadmap to identify synergies and appoint an organisation to be responsible for monitoring collaboration, with a reassessment in five years.	Aligned marine science strategies between governmental, NGO, and UKRI at different levels, in particular relating to Net Zero targets

	Engage with International Stakeholders	
INPUT	**RECOMMENDATION**	**OUTPUT**
International strategy documents	**Engage with international stakeholders, especially those involved in GOOS, to ensure consonance where appropriate.**	A 'living' UK marine science roadmap for aligning with international observing strategies
	Liaise with UK-IODP regarding future strategies for UK participation in ocean drilling over the next five years e.g., design of fleet to be able	

	to carry out site surveys, automation of smaller drill rigs, and efficient re-sampling of sites. After five years, reassess (through workshops and 'sandpits') whether the planned strategy is still aligned with principles of key stakeholder partners, as existing strategies adapt and evolve to encompass the wider use of emerging technologies.	
	Optimise ship usage	
INPUT	**RECOMMENDATION**	**OUTPUT**
Resourcing strategy International strategy Improved data ecosystem A fair, equitable and diverse UK marine science community Evolved fit-to-purpose view of marine science careers with expanded specialisms, including data and technology experts Improved capability for expedition planning	**Improve efficiency of ships over the next decade, for when ship-based activities are required.** Such developments will be facilitated through continued engagement with stakeholders over the next 5-10 years.	Low carbon or Net Zero ships and ship-based activities

	Increased bandwidth & Data ecosystem	
INPUT	**RECOMMENDATION**	**OUTPUT**
	Increase available bandwidth on existing ships to capitalise on remote participation in ship-based activities where possible.	Improved data availability Reduced travel to ships
FAIR data principles Resourcing strategy International strategy Evolved fit-to-purpose view of marine science careers with expanded specialisms, including data and technology experts	**Develop the data ecosystem over the next five years with clear compliance with FAIR principles, with the required meta data and machine-readability to enable to start the adoption of machine learning/artificial intelligence (AI).** Early adoption of cyberinfrastructure that is AI-ready will smooth the transition over the next decade to the more widespread use of smart sampling and digital twins. This development will require input from across UKRI Research Councils, including resources for data centres and advancement of emerging information technology.	An effective, flexible and fit-for-purpose data ecosystem, capable of supporting the future UK marine science community. Improved data availability Improved data quality control Improved processing power
Improved data ecosystem The next generation of UK ocean models	**Develop ocean digital twins.** Introduce funding calls across Research Councils (in particular NERC, EPSRC but also ESRC and MRC) over the next five years to promote the initial stages of a UK ocean digital twin network. Integrate digital twins into mainstream UK marine observations from 10-20 years.	Improved capability for expedition planning Improved capability for effective monitoring Improved capability for experiment planning

	Flexible hybrid system of "autonomy where possible"	
INPUT	**RECOMMENDATION**	**OUTPUT**
A fair, equitable and diverse UK marine science community Evolved fit-to-purpose view of marine science careers with expanded specialisms, including data and technology experts Resourcing strategy Improved data ecosystem Reliable platforms for long duration Reliable platforms for challenging environments (polar, deep, ice) New discipline specific sensors, remote sampling, and low carbon experimental design Low carbon or Net Zero ships and ship-based activities	**Develop a flexible hybrid system of "autonomy where possible" coupled with the continued operation of crewed research vessels over the next two decades, which can be made more efficient through improved co-ordination and data flow, would allow the UK to maintain their position as a world-leader in sea-going science and technology whilst also meeting Net Zero targets.** **Adopt new approaches flexibly and in parallel with rigorous ground-truthing, calibration and quality control in order to improve trust of the emerging technology in the community over the next two decades.** There is a need to ensure fair access to emerging technologies from the start, including an assessment over the next 1-2 years about how autonomous technology is costed into UKRI grants. Existing marine scientists need training in emerging technologies, in addition to recruitment of technology and data specialists over the next 5-10 years. There is a need to have conversations across sectors to ensure technology compatibility from the start.	A UK research fleet with the capability to serve multidisciplinary marine and to accommodate the wide range of both NMEP and user-supplied equipment needed to carry out world-leading marine research Removal of key barriers in the uptake of autonomous technology resulting in lock-ins from institutional learning effects, informational increasing returns, network externalities, and collective action

Further Work

In this report, we have identified some key targets for the next 5-10 years to help transition UK marine science into a Net Zero world, and "stretch targets" for the following decades that will require additional methodological development, beyond what is currently available or in the immediate pipeline. In addition to step changes required in terms of emerging technologies, there are a number of more challenging questions relating to more major shifts in the UK marine science landscape, or "ecosystem", that require more thought and investigation:

- **How will marine science career stages in academia and research look in the future? How does this fit into the shifting academic CV? Will training in new technologies be less challenging for early career researchers, in relation to mid-career and senior scientists?**
- **How will international collaboration and science diplomacy evolve into the future, and how will this influence the ability to utilise regional hubs and ship bartering?**

We recommend that a further assessment be carried out after five years to evaluate how the roadmap is progressing and whether any steers or direction changes are required:

- Is there effective communication between scientists and technology developers, such that there has been progress in the production of novel integrated platforms and sensors?
- Has there been successful alignment with international stakeholders, especially those involved in GOOS, to ensure consonance where appropriate?
- Have there been sufficient steps put in place to recruit and train specialists required for an effective future data ecosystem?
- Has there been successful coordination with industry and other private sector partners to take advantage of technology already under development and to open up new opportunities?

Future Engagement with other Key Stakeholders

The success of any Net Zero oceanographic capability vision is going to hinge on strong communication with the UK and international marine science community. In addition to liaising with international partners to ensure effective collaboration, it will be essential to keep the UK science community up-to-date with new directions and approaches, allowing effective feedback from a range of users from a range of disciplines and career stages. As the developments come online, they will only be taken up into wider usage if they are trusted by the scientific users, requiring continual dialogue surrounding calibration, quality control, accessibility and costs.

Further discussions with industry representatives are likely to be fruitful, to follow up on the opportunities identified in this report.

Implications for Equality, Diversity & Inclusion

At present, there are a number of barriers that can limit the participation of individuals with medical issues or disabilities, or real or perceived caring responsibilities, in observational marine science.

For example:

- In the UK, seagoing marine scientists must pass the ENG1 medical examination set by the MCA in order to participate on a research cruise.
- Caring responsibilities may limit the involvement of individuals, making them unable or unwilling to spend long periods of time away from home.
- Perceived limitations, including expectations of traditional family roles, may limit opportunity for individuals who would otherwise be interested in seagoing science.
- Cultural expectations tend to persist even after explicit barriers are removed. Historically, women were explicitly excluded from seagoing and Antarctic service[35] and these cultural expectations can take a generation or more to shift.

These barriers can affect both current members of the marine science community as well as the population of potential marine scientists who may see a career in marine science as incompatible with their lifestyle or responsibilities. We note that the data used to define the current usage of ships, the workshop participants and survey respondents largely reflect the views and practices of seagoing marine scientists. This is a particular sample of individuals have not been prevented from participating by the barriers currently in place, and so will be less likely to capture the views of people who have been excluded from the community.

Depending on the path forward towards Net Zero, there will be implications for equality, diversity and inclusion in observational marine science. In a future scenario with a move towards more autonomous capability (e.g., in the "hybrid model" outlined in the section "Implications for net zero vs do nothing"), we may be both moving towards net zero and also removing or reducing an existing barrier to participation. With autonomous vehicles, scientists may no longer require an ENG1 certificate nor long absences away from home in order to participate in observational marine science. As an example, long deployments of autonomous underwater gliders may only require a week's travel and a day on a vessel in order to deploy and to recover the instrument in a near-shore environment or, alternatively, deployment can be carried out by skilled technicians with scientists remotely participating. Much of the data analysis that might otherwise take place in real time on a ship, can instead take place in near real-time from an office on land.

A shift towards autonomy and robotics might also be accompanied by increased barriers to participation. At present, the robotics and engineering communities are male-dominated, and there is a cultural expectation that these fields are less available or open to participation by women. This can be seen, for example, in the gender distribution of workshop participants for NZOC workshops 2-6. The shift towards autonomy could also present new barriers to access for other underrepresented groups. As autonomy and robotics become more integrated into observational marine science, cultural expectations around the use of robotics may present a new real or perceived barrier.

Finally, the current practice of seagoing to collect observational data may also contribute to the diversity of the marine science community. Individuals who are unwilling or uninterested in an office-based job performing data analysis, but are attracted to the adventure and excitement of a

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[35] Hendry et al., 2020, Equity at Sea. Ocean Challenge. https://www.challenger-society.org.uk/oceanchallenge/2020_24_2.pdf [*Accessed January 2021*]

career with time in the natural environment, have likely broadened the diversity of perspectives in the marine science community.

It will be essential to establish a practice of monitoring equality, diversity and inclusion as the path towards net zero is undertaken, to evaluate what expected and unforeseen consequences may be occurring as technology-based decisions are made.

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Appendices

Appendix 1: Working group one (WP1) terms of reference (ToR) and objectives

Terms of reference

1. Identify the science requirements for a future national oceanographic research capability (ideal case) using historic use data and stakeholder engagement.
2. Consider the interplay between international ocean observing (for all stakeholders / users) and national capability and its effect on future requirements.
3. Consider the impact that not having access to a large research ship would have on the delivery of science.
4. Horizon scan for changes in scientific priorities.
5. Explore what our future scientific priorities may be and the impact on the UK's global positioning of reduced access to a large research ship.
6. From a science perspective, seek to identify possible alignment of oceanographic research with research, development and innovation objectives.

Objectives

Science requirements & international observing (Terms of Reference (ToR) 1-3)

- Parse historic use data (past 5-10 years of cruise reports/SMEs, phase 0) to identify how ships are used now.
- Sift through 'international ocean observing' strategy documents to capture identified priorities and directions.

Horizon scan future science needs in context of net-zero research vessel (ToR 1, 4, 5)

- Engage with marine researchers across the sector (HEIs, research institutes, civil service, industry) via focus groups (phase 1), online workshop (phase 1) and follow-up online survey (phase 2-3)
- Produce final report as deliverable (phase 4)

Alignment with RD&I (ToR 6)

WP-specific Critical Success Factors (CSFs)

- Engagement with full diversity of researchers across all relevant marine subject areas
- Engagement with national and international networks

WP-specific risks identified

- The project may not involve the appropriate breadth of scientific disciplines or industry/civil service
- HEI or research institute commitments (e.g., teaching) may hinder participation

Appendix 2: Case Studies of Global Observing Bodies, Systems, Networks and Development Programs

Partnership for Observation of the Global Ocean

Partnership for Observation of the Global Ocean (POGO)[36] was formed in 1999 by major oceanographic institutions, and is regulated by (and reports to) the Charity Commission of England and Wales. The organisation is based on three "pillars": Innovation in ocean observing, capacity development, and outreach and advocacy.

POGO state their priorities as follows.

1) *"Lead the making and innovation of observations that contribute to the global ocean observing system"* through:

- Rapid development and adoption of "emerging and transformative" technologies;
- Expanding the observing systems especially biological and biogeochemical parameters;
- Engaging with agenda of the Decade of Ocean Science for Sustainable Development.

2) *"Develop the world-wide capacity and capabilities needed for ocean observations and nurture new generations of scientists, technical experts and leaders in ocean affairs."*

3) *"Advocate and promote in our own countries and world-wide (to inter-governmental organisations, governments, funding agencies, businesses, foundations and citizens) the importance of making systematic sustained, ocean observations for the advancement of science and for informed, sustainable management of the ocean for the well-being of all humankind and making the case for securing the necessary funding resources to achieve it"* through:

- Broadening membership and extending geographical coverage;
- Engagement with a diverse range of partners including business and industry; enhance skills and capabilities.

Key POGO activities include: the support of Lagrangian float and drifter programs (e.g., Argo); fixed long-term monitoring sites (e.g., OceanSites); development of low-cost sensors and systems for coastal ocean observing (e.g., OceanMods); development of emerging technologies for biological observation, fellowship and training programs; and outreach and education materials.

The Global Ocean Ship-Based Hydrographic Investigations Program

The Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP)[37] panel was established in 2007, to develop a strategy for a sustained global hydrography program to replace and update previous efforts (e.g., World Ocean Circulation Experiment, WOCE). GO-SHIP has a number of aims:

To bring together international researchers interested in physical oceanography, marine biogeochemistry and ecosystems, and other end-users of ocean interior datasets;

- To coordinate a global network of sustained hydrographic sections (in association with GOOS);
- To promote best practice for collection of oceanographic data;

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[36] https://pogo-ocean.org/ [*accessed October 2020*]

[37] https://www.go-ship.org/ [*accessed April 2021*]

- To act as a source of global data, incorporated into JCOMMOPS for increased data usage; also useful for calibration of existing autonomous platforms (Sloyan et al., 2019).

Case Studies of Regional Observing Systems

Whilst there is a clear need for worldwide ocean observing systems and international coordination for fit-for-purpose research into global processes and international coordination and participation, there is also a requirement for more regional based observing systems that recognise localised phenomena, unique geographic characteristics, and endemism. Such regional observing systems must be designed in the context of global systems, for effective integration of data and information.

Southern Ocean Observing System

The Southern Ocean plays an essential and disproportionate role in global climate, connecting the global ocean and regulating the transport of heat, salt, carbon, and nutrients. The Southern Ocean Observing System (SOOS) was established to address key scientific questions in the Southern Ocean[38], with support from the Scientific Committee on Oceanic Research (SCOR), the Scientific Committee on Antarctic Research (SCAR), and other organisations including POGO and GOOS. SOOS is based on the FOO principles of sustained, multi-disciplinary observations, with the recognition that new technologies are needed, especially in observing biochemical and biological variables, and that there are advantages in broadening participation e.g., through the Voluntary Observation Ships (VOS) Programme (Table 6).

Key SOOS strategy properties	• Sustained • Feasible/cost-effective • Multidisciplinary • Targeted to specific scientific questions • Integrated with global ocean and climate observations • Based on proven technologies but with ability to evolve • Integrated with data management • With end-users at centre of design • Built on past, current and future research projects

Table 6: Key strategies of the Southern Ocean Observing System.

SOOS place an emphasis on their data strategy, promoting open access, the use of existing data centres, improvements in access to archived data, best practice and protocols, and developing a data portal (SOOSmap).

Key SOOS activities also include networking activities carried out by working groups (regional and themes/methods) e.g., production of synthesis publications, workshops, and joint funding proposals (Newman et al., 2019; Rintoul et al., 2012).

Arctic Region Component of the Global Ocean Observing System

An Arctic Region Component of the Global Ocean Observing System (ARCGOOS) has been proposed to improve understanding, monitoring and prediction within one of the most rapidly changing regions (Lee et al., 2019). The identified aims, following FOO approaches to build a requirements-

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[38] https://www.soos.aq/ [*Accessed April 2021*]

based framework, are to ascertain societal benefit areas (SBAs), used to define the science and operational objectives; these objectives are then used to identify the key variables, which are then weighted for readiness and feasibility to produce the "essential ARCGOOS variables" (i.e., equivalents to EOVs that are geared specifically for the Arctic environment).

ARCGOOS – as an endeavour – is based on the principles that it would identify and fill critical thematic, regional and trans-sectoral gaps; integrate remote sensing and *in situ* observations; provide open data (and better use of historical data); be governed effectively under Sustaining Arctic Observing Networks (SAON) and the International Arctic Science Committee (IASC); and co-produce research with Indigenous rights-holders (Smith et al., 2019).

European Marine Board and the European Ocean Observing System

The European Marine Board (EMB)[39] is a self-funded, independent, non-governmental advisory body with the object to facilitate transfer of knowledge between the scientific community and decision makers (Table 7). The EMB places key emphases on promoting communication and understanding on the following topics:

- Ocean being a 3D space over time i.e., 4D ocean, with spatial and temporal interplay between ocean physics, chemistry and biology;
- Multiple stressors;
- Extreme events;
- New technologies;
- Fostering sustainable science.

Key EMB principles	• "Policy-led and solution-orientated" agendas • Co-production of knowledge with stakeholders • Inter- and transdisciplinary research • Appreciation of Earth-system complexity • Focus of communication and research activities at a local level • Facilitate social learning rather than definitive answer • Scientific diplomacy • Coupling with economic and social sciences

Table 7: Key principles of the European Marine Board.

The EMB and GOOS (and regional partner EuroGOOS) established the European Ocean Observing System (EOOS)[40] in 2018 as "*a coordinating framework to align and integrate Europe's ocean observing capacity, to promote a systematic and collaborative approach to collecting information on the state and variability of our seas, and to underpin sustainable management of the marine environment and its resources*." The aim of EOOS is to strengthen existing links, and contribute

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[39] European Marine Board (2019) Navigating the Future V: Marine Science for a Sustainable Future. Position Paper 24 of the European Marine Board, Ostend, Belgium. ISBN: 9789492043757. ISSN: 0167-9309. DOI: 10.5281/zenodo.2809392; https://www.marineboard.eu/ [*Accessed April 2021*]

[40] EOOS Strategy and Implementation Plan 2018-2022 released. http://www.eoos-ocean.eu/eoos-strategy-and-implementation-plan-2018-2022-released/ [*Accessed October 2020*]

towards the EU Marine Strategy Framework Directive, and the Common Fisheries Policy[41], with a strong focus on inclusive and sustainable science, stakeholder/community input and co-production of research (Jetz et al., 2019).

Case Study of National Marine Program Strategy: The National Marine Science Committee (Australia)

National marine programs release periodic strategy and priority documents, which contain relevant (often recurring) themes relating to future science delivery approaches and steps. The Australian National Marine Science Committee[42] is an advisory body established in 1998 (originally as the Oceans Policy Science Advisory Group under Australia's Oceans Policy). The aim of the National Marine Science Committee is to connect scientists at research institutions and universities with stakeholders in various levels of government and within the broader community. Their recent National Marine Science Plan (2021-2025) emphasised the need for an increase in research infrastructure spending, international collaboration, and stakeholder collaboration and consultation. The Science Plan identified seven key grand challenges and steps to success (Table 8). The approach to this near-future science plan focused on the need for sustainability, funding of research infrastructure, long-term monitoring and baseline development, co-ordinated national studies and modelling systems, effective training and open data in order to deliver a coordinated science program to support decision-making by policy makers and other stakeholders.

Grand Challenges	10-year steps to success
Marine sovereignty and security Energy security Food security Biodiversity conservation Sustainable urban coastal development Climate change adaptation Resource allocation	Decision-support tools Models and forecasts Industry and government partnerships Cross-discipline skills Research vessels Exploration, mapping, monitoring Marine baselines National collaborations

Table 8: Grand challenges (left) and steps to success (right) as identified by the Australian National Marine Program Strategy.

Deep Ocean Observing System

The Deep Ocean Observing System (DOOS)[43] was established to address the challenges of extending the GOOS approach, science questions and definition of EOVs (physics, biogeochemistry and biology/ecosystems) to the deep ocean[44], given that the GOOS defined Biology & Ecosystem EOVs are mostly relevant for shallow waters (ecosystems supported by mangroves, seagrass etc.). The overall aim of DOOS is "*to improve understanding of the state of the deep ocean with respect to baseline conditions, response to climate variability and response to human disturbance*", aligning with FOO and GOOS principles as described above. A Blueprint for a Global Deep-Sea Ocean Decade Field Program was recently published, aligning DOOS and other strategic approaches (e.g., General

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[41] Note that, whilst the UK is no longer in the EU, UK scientists are eligible for Horizon Europe funding. Strategic funding may be available to address specific interests of the EMB and EOOS.

[42] National Marine Science Plan 2015-2025: Driving the development of Australia's blue economy. www.marinescience.net.au. [*Accessed October 2020*].

[43] https://deepoceanobserving.org/ [Accessed May 2021]

[44] defined as generally much greater than 200 m and preferably greater than 2000 m

Ocean Survey and Sampling Iterative Protocol – GOSSIP - see other stakeholders), to plan effective deep ocean surveys specifically for the UN Decade of Ocean Science for Sustainable Development, using new technologies where possible for data acquisition and extraction (Howell et al., 2020). This blueprint proposed a “stratified” survey based on the following criteria: biogeographic region, depth, horizontal distance, substrate type, high and low climate hazard (early/late time of climate change emergence), and anthropogenic pressure (fished/unfished, near/far from sources of pollution, licensed/protected from industry activities). Both spatial investigations and timeseries are required, focusing on poorly surveyed regions including the polar regions, deep ocean (greater than 2000m) and midwater ecosystems; survey sites also need to be selected on the basis of the availability of existing observing infrastructure or opportunities for new and effective infrastructure. Physical samples are required for taxonomic and genetic work, and sample collection, preservation and archiving must be carried out following the CARE (Collective benefit-Authority to control-Responsibility-Ethics) principles.

International Ocean Discovery Program

The FOO and related GOOS frameworks focus on oceanic observations within the water column and at the seawater-seabed nexus. However, several important areas of research require the sampling of deep marine sediments and bedrock, frequently overlooked by international ocean observing strategies

One of the largest international programs for ocean coring and drilling is the International Ocean Discovery Program (IODP, previously International Ocean Drilling Program)[45]. Whilst IODP is a global organisation, and does not use the UK NERC/BAS ships for drill deployment, there is a UK branch (UK-IODP) and key synergies that relate closely with the use of UK marine research infrastructure, including the use of ships for critical site surveys. Furthermore, smaller drill rigs (e.g., owned and operated by the British Geological Survey) can be operated on NERC/BAS ships, and are involved in EU platform-specific drilling programmes.

IODP released a strategy document in 2020 (Coppers and Coggan, 2010[46]), detailed their ‘enduring principles’: open access to samples and data; standard measurements; bottom-up proposal submissions and peer review; transparent regional planning; promoting safety and success through site characterisation; regular framework assessments; collaborative and inclusive international program; enhancing diversity.

They identified four ‘Enabling elements’ to achieve their goals:

- Broader impacts and outreach;
- Land-to-sea drilling collaborations;
- Terrestrial to extraterrestrial i.e., collaboration with space scientists and space agencies;
- Technology development and ‘Big Data’ analytics.

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[45] https://www.iodp.org/ [*Accessed April 2021*]

[46] Koppers, A.A.P., and R. Coggon, eds. 2020. Exploring Earth by Scientific Ocean Drilling: 2050 Science Framework. 124 pp., https://doi.org/10.6075/J0W66J9H [*Accessed April 2021*]

Appendix 3: Full workshop report

Introduction

On 27th January 2021, the first Net Zero Oceanographic Capability (NZOC) workshop was held to engage with stakeholders on the future of UK marine science. The workshop, 'The 21st Century Marine Scientist - Delivering science in a net zero world', provided an opportunity for stakeholders to discuss the multiple science drivers that will help to shape future UK oceanographic research directions and infrastructure investment over the next 15 years, and how investment decisions may also be shaped in turn by the need for sustainability and a low carbon footprint.

Science drivers

There is a need to move from broad correlations to understanding connections, processes, and mechanisms in order to have predictive power and confidence.

Approaches to ocean science fall broadly three categories:

Process studies - understanding the mechanisms behind - and spatial/temporal scales of - oceanic processes, and their interconnections;

Sustained observations - improving knowledge of system change;

Forecasting – obtaining data for initialization or assimilation in forward stepping.

Common themes of science drivers

Climate linkages

Interactions between ocean and climate, in particular tipping points, are key to demonstrating climate model forecast accuracy (i.e., public confidence in climate change predictions).

Examples of tipping points that we need to investigate more include stability of continental ice sheets, monsoons, sea-level change, ocean circulation and response to changes in the hydrological cycle, changes to nutrient supply, primary productivity and ecosystem response.

We need to understand the local and regional effects and patterns on these cycles and processes, and the potential for impacts to cascade to more global scales.

We need both current observations but also archives of past change, to i) determine baselines and ii) recognise and understand the scales of tipping points in the climate system.

Access to under-observed regions

There are a number of marine environments that are challenging to observe, resulting in important gaps in existing datasets and in our mechanistic understanding of oceanic change.

The polar regions are difficult to access, and are under-sampled and under-constrained. However, the Arctic and parts of the Antarctic are experiencing some of the most rapid climate changes in recent decades. Parts of the Arctic are also challenging to access for geopolitical reasons. This has left us with some key outstanding questions:

What is the impact of rapid changes in the Arctic system on the UK ecosystem services?

How are changing sea ice dynamics going to influence brine rejection and deep water formation?

How are changing sea ice dynamics going to influence ecosystem structure?

What will be the impact of the opening up shipping lanes?

How will the melting of polar glaciers impact coastal waters physically and biologically?

The deep ocean is also difficult to access, with resulting gaps in process studies and observations. However, the seabed is increasingly being targeted for economic purposes including communications cables, carbon sequestration and waste storage, and extraction of natural products (minerals, metals, pharmaceuticals), and we need to understand the potential impacts of these activities on the ocean system.

Ocean interfaces

Critical processes are active at the interfaces of the ocean**,** including the ocean-atmosphere, ocean-ice, and ocean-seabed locations, which are often climatically sensitive and respond rapidly to change. We need to understand how climate change is affecting these interfaces (e.g., land to sea, permafrost and release to oceans and atmosphere, ocean to atmosphere, ocean /sediment interface).

These areas of research are often not well covered by a single science discipline, and require a multidisciplinary approach, and the appreciation of the interactions between biology, chemistry and physics.

Carbon cycling, biogeochemistry

We need to improve observations and mechanistic understanding of the carbon cycle from the atmosphere to the benthos, including controls of reactions, rates and fluxes, leading to improved models founded on quantifiable processes rather than empirical relationships. To do this, we need high-resolution (spatial and temporal) data of dissolved and particulate organic carbon, and a better understanding of sinking processes and linkages with biology and physics.

Some outstanding questions in this field are:

Is the marine pool of dissolved organic carbon (DOC) in steady state? Why is this so? What processes control this outcome?

What is the fate of carbon (both terrigenous and marine) in the ocean and sediments?

What controls the fragmentation of sinking particles in the ocean?

What are the processes for two way vertical travel in the carbon pump?

What are the time scales of capture for different sinkage depths?

What determines the time period of carbon storage?

What are the impacts of gross sinking processes (whale falls, debris, plastic, wrecks, sunk post 2nd world war ships)?

We need to take a more holistic view of biogeochemical cycling, including a better understanding of the roles of organisms (including microbes) on biogeochemical cycles and, conversely, the impact of ocean stoichiometry (nutrient ratios) on the distribution of organisms. The impact of anthropogenic activities on biogeochemical cycles is a broad challenge, including nutrients to pollution (plastics, acidification), the impact of changes in temperature and salinity on biogeochemical cycling, and potential consequences of carbon sequestration and natural resource extraction. We still do not understand the individual effects of these, let alone their interactions, on global biogeochemical cycles.

Conservation

The health and condition of marine organisms is critical for ecosystems and ecosystems services. There is a need for understanding processes within organisms (e.g., gene expression, symbiotic relationships), organisms-organism interactions, and how organisms and ecosystems will adapt to changing environments, especially under the influence of multiple stressors. We need to understand the vulnerabilities of and risks to these ecosystems from climate change on a variety of time and spatial scales; impacts on population connectivity; species, population and ecosystem recolonisation potential at different rates of change and in different environments; and consequences for fisheries.

The UK has a strong leadership role in understanding, baselining, monitoring and protecting large maritime protected areas (MPAs), including in British Overseas territories. The establishment of environment baselines and long-term observations will be critical in assessing the success of MPAs to protect the world's oceans into the future.

Society and the ocean

Society will have more to do with the oceans in the future in nearshore, offshore and blue oceans, to source resources (energy, minerals, precious metals and food) for a growing population. These will need to be monitored and understood, with action taken to ensure sustainable development.

Monitoring of ocean health is critical, but capabilities, responsibilities and approaches are yet to be agreed. Coastal regions are of particular importance, due to their proximity with human population centres.

Outstanding questions include:

What is the future of food security, and how can it be maintained?

What is the impact of noise pollution on marine systems?

How will the drive towards "Net Zero" impact decision-making in marine policy (including exploitation of oceanic energy resources (geothermal, tidal) and extraction of precious metals by deep-sea mining)?

Can marine resource acquisition be carried out sustainably?

How can the ocean be used to store carbon and hydrogen more effectively and safely?

Should science priorities be informed by anthropogenic impact, or can priorities still be science-focused (blue skies) for the goal of discovery?

What are the new opportunities and solutions that a greater understanding of marine science can provide for society?

Geohazards and risk management

Geohazards, including underwater earthquakes and landslides, are likely going to have an ever increasing impact on coastal communities, especially those also impacted by sea-level rise and coastal erosion. We need a better observation system – preferably with real-time monitoring – to be able to assess risk and devise mitigation strategies.

Understanding the circulation of the mantle through higher-resolution observations will help to address the poor understanding of, for example, slow spreading Arctic ridges and seafloor heterogeneities, and will result in better quantification and prediction of geological risk and long term processes.

How can we capture the infinite range of scales needed to be measured?

Future marine research will have to reach across a range of temporal and spatial scales, from high-energy small-scale processes to averaged large-scale trends and cycles, resulting in a significant challenge for how the key interrelated questions are addressed. Multidisciplinary and holistic approaches will be required, encompassing more than ocean science (e.g., also atmospheric science, terrestrial studies, social sciences, economists and humanities).

The importance of communication

Effective messaging of climate crises implications and mitigation will be key to manage effective interaction with stakeholders and rights holders, including communities, industry, and policy makers.

Data requirements

Common themes of model data requirements

Improved model validation

Larger spatial and temporal model validation and data assimilation is needed at a variety of scales, especially in the parameterisation of processes over a range of scales, such as sub-grid scale and interface processes, e.g., ocean biology and biogeochemical cycles. We need to move away from representing biogeochemistry and biology in models using empirical relationships towards mechanistic representation of processes.

Better collaboration in study design

We need to foster better connections when planning observational programs, both in terms of efficient use of ships, autonomous instruments and remote sensing, and in terms of the connectivity between observational and modelling data. Models can be used to inform observing systems (e.g., collecting data at the right place and the right time), and would mutually benefit from research co-design and co-production. This is particularly true when a high-resolution four-dimensional view of the oceans (and atmosphere) is needed: full observations may not be possible (even with autonomous technology) requiring a flexible and adaptive sampling strategy. Similarly, measurements could be targeted at model uncertainties and potential feedback processes, especially in relation to processes and interactions. All data streams (observations and models) could then be integrated and made end-user friendly.

Common themes of general data requirements

Increased data acquisition

Ships and autonomy can be used in a complementary way, opening the door to more multidisciplinary studies and greater efficiency ("Visit once, measure more!" instead of "measure once, use more"). However, with the likely rise in the use of autonomous vehicles across the disciplines, we will require longer-term, fully-integrated measurements, and real-time, high-resolution four-dimensional data for effective forecasting. There will be a consequential increase in data acquisition. Furthermore, we need to cover gaps in observational data, from difficult to access places and critical sampling periods at certain times of year that have previously been limited by logistics or weather conditions.

Data management/accessibility

Data management is critical, and will need a renewed approach with an increase in autonomous observations and integration with ocean models ("digital twins").

Data (or a subset of the data) will need to be accessible in real-time (or near real-time). Data centres should be involved in the research from the start of proposals, so that data management approaches are consistent (and potentially automated and decentralised).

Raw data should be kept in data centres with the aim of allowing post-processing with new technologies as they arise.

Data should be easily accessible and usable, in common formats, and researchers should have the ability to interact with the data in real-time and at any point.

Use of existing data

There should be a push to get the most out of the data that we already have available. A lot of data is collected but under-used. The use of new technologies (see below) could be used for data-mining and data "hacks". The value of existing datasets should be enhanced through the continuation of time series observations.

Data should be made widely available to the community free of charge, potentially also sharing in data infrastructure and processing code to deliver "information" as a public good to the broader society.

Transformational Technologies

We need to take advantage of emerging and transformational technologies to build a flexible and adaptable observation system that has the capacity to react as science questions change.

Common themes: a "wish list" for marine scientists

High-resolution and fully integrated real-time measurements

An understanding of the physics of the ocean would be transformed by being able to measure the density and velocity field at all points in the global ocean, at every grid point of a model, simultaneously. We need means of measurements that do not "constrain" the ocean but let it "speak".

Whilst the technology to do this is a long way off, there are some emerging approaches that could allow for high-resolution and wide coverage of data gathering (e.g., high frequency radar for surface currents). Passive and active acoustic tomography could be used to determine the internal structure and measure density and current in three-dimensions, without interfering with biology.

Biogeochemistry would also be revolutionised by high-resolution (spatial and temporal) measurements of dissolved and particulate phases in the water column and at the seafloor. For example, perhaps particulate organic matter or microplastics, could be measured in the three-dimensional ocean - perhaps using some acoustic technique - in line with similar remote sensing methods used to assess air quality in the atmosphere. Such approaches could additionally be coupled with release experiments to obtain the parameterisations required to integrate biogeochemistry into models.

These approaches will require high-bandwidth, long-range, through-water telemetry for data transmission. Real- (or near real-) time data could be assimilated into ocean models (a "*digital twin*" *of the ocean*) for the purposes of observing system planning, process studies or forecasting, or improving confidence in weather and climate change projections.

Mapping the entire seafloor: Making seafloor maps is often a starting point and enables part of marine science expeditions across all disciplines. Fully autonomous mapping of the ocean, seafloor and subsurface would be invaluable, as would a spatial map of bottom water pressures.

Multidisciplinary timeseries: Multidisciplinary timeseries could collect a wide range of data types (physical, chemical and biological) alongside sampling efforts, with regular retrieval and data extraction, aiding process studies and adding to sustained, long-term observations. More capability could be added to existing activities by linking disciplines and bringing in international partners.

Subject specific sampling technologies

Biology. Biological monitoring and sampling will continue to be key into the future, in order to determine the biological indicators of change at the individual, species, and population levels, and changes in habitats.

Transformational technologies to support these studies could include expansion of eDNA approaches, tagging methods, use of taxonomic and DNA libraries/bar-coding, photography/imaging, Passive Acoustic Monitoring (PAM), high-resolution satellite data, and the use of adaptive sampling. Automated sampling would require a means of *in situ* preservation (using different preservation methods), and sampling live organisms under *in situ* conditions (temperature and pressure) for subsequent experimentation.

'Omics' technologies could be transformational for determining rates of biological processes and organism interactions/behaviours, which has to date been more challenging.

Geology. Imaging, profiling, and sampling of sediments and seafloor rocks will continue to be important, targeting a variety of different sediment and rock types and conditions (contourites, vent sites, abyssal plains, coastal and continental shelves, etc.).

Transformational technologies to support sediment studies could include *in situ* measurements of microbial activity (e.g., eDNA), porewaters (nutrients, metals, dissolved organics) and dissolved gases (methane, hydrogen sulphide). Seismic reflection and electrical resistivity methods for soft sediments could be deployed from automated landers, needing a range of frequencies for a range of resolutions and penetration depths (potentially increasing depth of penetration beyond what it currently possible).

Sampling of sediments would require a means of *in situ* preservation (using different preservation methods e.g., pressure and temperature control, freezing, anaerobic conditions etc.).

Solid earth geophysics could be advanced through robotic deployment of ocean-bottom seismometers (OBS) and resistivity meters.

Subseafloor coring and drilling (wireline) could be improved to sample and log currently challenging materials e.g., hard/broken/fractured rocks, sands, gas hydrates. Seafloor holes could be used for observatories and experimental stations (microbial, chemical, mineral stability, deformation, high temperature and high pressure, eH, pH extreme environments that are difficult to replicate in laboratory).

Automated platform and sensor technologies

The oceans and climate are changing at a rapid rate. To assess rates of any anomalies relative to a baseline, we need cheaper and smarter observation technologies, with low power systems able to carry out longer deployments that are less reliant on ships. Richer data streams are needed to make observations scalable in the ocean, where measurement range is constrained compared to sensors used on land. We also need to advance modelling methods and utilise artificial intelligence methodology to facilitate efficient, adaptable and flexible observing systems.

Platforms

Autonomous Underwater Vehicle (AUV) swarms. Renewable (self-charging or charging through "hubs") and adaptable powered instruments with appropriate navigational tools would be invaluable for measuring at high-resolution for long periods, and could be used with ships to expand the "footprint" of sampling (e.g., the use of drones to deploy XBTs away from a ship). High-resolution, large-scale arrays of "fleets" ("Argo Plus") would allow the bridging of different spatial and temporal scales.

Efficiency would be increased through the use of intelligent sampling rather than passive or pre-programmed sampling. Safety would also be increased if hazards could be avoided using the same technology. Dormant technologies (i.e., "waking" unpowered AUVs waiting in a particular location, using a signal) could also be used for the efficient observation of a specific event. This would allow the real-time monitoring of events at large scales connected to high resolution swarming systems that can be deployed quickly to explore a particular process.

AUV technology should also be developed for challenging locations e.g., deep sea, high currents, Arctic/Antarctic/under ice.

Recharging "hubs" could also be used as data caches for improved data security.

Autonomous Surface Vehicles**.** ASVs, such as Saildrones, could be used for automated measurements of key parameters (e.g., heat and gas fluxes, radiation, etc.). Saildrone-like vehicles could also be used as an efficient, low energy means for sample transport from "repositories", or hubs for recharging other vehicles.

Underwater observatories. Static observatories in the ocean could be used as moored platforms for *in situ* observations, mesocosm/process/incubation experiments, recharging and maintaining autonomous underwater vehicles (AUVs), data transfer, deployment of "rovers" or "swarms" of AUVs, "crawlers" or movable benthic chambers. A global network of such observatories would revolutionise understanding of the interconnections in the deep sea.

Other platforms. Reducing the cost of the platforms will increase the number of observations we could make and would help to democratise ocean observing. Ideas for other low cost and efficient platforms include:

Modular measurement platforms/floating laboratories;

Airships;

High Altitude planes;

Drones;

Offshore ‘power’ stations for recharging AUVs;

Old/existing infrastructure e.g., offshore wind farms.

Satellites/remote sensing

The use of satellites and other remote sensing aerial methods (e.g., rotary, fixed wing and balloons) could be expanded, including using new satellite products on different tracks and at higher temporal resolution and finer spatial-scales, finding new methods to analyse different key parameters (e.g., gases, biogeochemical processes, pollution). More, smaller remote sensing devices could be used to improve resolution.

New remote sensing methods could also be developed to see beyond the sea surface, and to improve calibration.

New sensors

Novel, small, lower power, accurate and precise sensors – used on the platforms described above – would transform ocean observing.

New measurements. The development of more lab-on-chip, micro-fluidics etc. sensors would transform the measurement of physical properties and dissolved and gaseous constituents of seawater, in particular for use in biogeochemistry (e.g., carbonate parameters, Eh, methane, nutrients, micronutrients), biology (e.g., acoustics, ‘omics’, eDNA, novel biomarkers), and physics (e.g., heat flux). Miniaturised tagging technology would help in a number of biogeochemical and biological applications (e.g., individual zooplankton, organic matter particles).

“Biosensors” - using organisms to sense the environment – could be used for novel applications.

Higher-quality measurements. In addition to improving precision, accuracy, and calibration, there would be significant advantages to developing self-maintaining/cleaning, self-calibrating, self-deployable, and self-powered sensors.

More sensors per platform. The development of lower risk, smaller, cheaper sensors would reduce risk (e.g. with loss of an instrument) and allow more sensors per platform/instrument thus enabling better resolution.

Multifunctional systems

There is a need to promote the use of re-deployable, multi-functional observation systems that can go to a location to perform different tasks (i.e., become full laboratories). It is important to develop systems that can be tailored to specific observation needs (e.g., subsurface probing, or deep ocean, or under ice) without making them bespoke to the extent of being single user systems. These systems would be high power, high bandwidth, and high complexity platforms, but could be long-lasting, run on renewable energy and efficiently use smart technologies.

Use of Artificial Intelligence (AI) in ocean data science: Machine learning or AI development and integration with automated platform, sensor and sampling technologies would allow for easier and quicker ocean data availability, and add potential to the goals of efficient/smart/optimised planning and observations, real-time monitoring at a range of spatial scales, and rapid quality control. Data centres could be established with links to remote telepresence for understanding ocean observations as they occur, allowing intelligent filtering tailored to personal interests, and expert intervention in subsequent observations made autonomously or by operators in the field. AI could also be used for more effective mining of existing data, and aggregation of different data streams through time for a particular location.

Transformational technology in modelling: Transformational modelling methods (e.g., adaptive mesh), together with AI methods, would allow i) *model uncertainties to be addressed* and ii) for the *full integration of models with high-resolution observations*, creating a "digital twin" of the oceans for development of baselines, detection of anomalies, forecasting etc. Observations could be planned (e.g., AUV deployments) according to model predictions to address largest uncertainties, errors, and data gaps.

It would be possible to observe rigorously at very small scales- within a typical model grid cell - and train AI to emulate/simulate subgridscale processes. These next generation models could also be used to better represent currently challenging environments e.g., nearshore, shelves, polar regions.

Technologies in education/communication: Lastly, the transformational technologies described above could also be used to enhance outreach and education capabilities on a global scale, making the oceans accessible and improving ocean literacy. Ideally, this could be incorporated into curriculum changes, to help change the narrative of ocean science, and reaching out to the next generation of ocean scientists from an early age.

Interconnection of Different Technologies

Improving efficiency: It is likely that there are some activities that can only be carried out on a ship. To improve efficiency and value for money, we need to coordinate usage and do "*more from the ships when the ship is doing things that only ships can do*". This could be achieved by combining and interconnecting the different new technologies, for example through deployment of smart and adaptable autonomous vehicles (aerial, surface, marine, submarine, subsurface) and sensors, with deployment planned using coupled models or "digital twins" and AI. We also need to widen access to the ships, which could be supported by changes to current funding structures (e.g., smaller "add-on" grants to carry out complementary research on an existing cruise).

Power and energy: We recognise that the answers to many of the questions surrounding the use of transformational observing systems will lie in i) *new technologies for power supplies*, such as batteries, recharging technologies, moored charging platforms, and ii) making *ships more energy efficient*, utilising recycling and heat recovery and reducing waste (to maximise science output per unit of carbon input). New science ships should be opportunities for clean technology development, and experimentation with efficient and adaptable modular systems.

Links with communications/computer technology/broader automation technologies: Use of computer technology - for example from machine learning, gaming and virtual reality - could be used to improve Human Machine interfaces (HMI) and visualisation of science outputs to aid interpretation and communication of four dimensional data from different disciplines and across a range of temporal and spatial scales.

Including the technology community would help with knowledge transfer for software skills and coding for creation of visualisation, which could perhaps be encouraged through the employment of marine science Research Software Engineers.

Known Unknowns

Trends in Sectors

Decline in oil and gas. The current decline in oil and gas industry will reduce a significant area where marine technology development occurred at scale. This is unlikely to be filled by science and academia due to their being a relatively small and esoteric application. We will likely need to develop new models to fund technology development.

Increase in environmental management. It is possible that increased focus on environmental management will provide new opportunities for development. See, for example, the Saildrone model.

Legal implications of autonomy. At present, it's unclear what the legal and regulation changes will be with regards to remote piloting of marine platforms. What are the consequences of causing collisions or being hit by marine traffic?

Trends in Technology

Trends in vessel energy systems. It's likely that research ships will follow trends in industry vessel energy systems.

Communication capabilities. Improvements in satellite-based communication systems may enable higher bandwidth data rates from ships/platforms at a lower cost.

Cloud-based computing. New approaches in cloud-based computing may enable data from platforms/ships to go straight to the cloud to be analysed in real-time. How can we ensure stewardship and curation of the data collected now for the future?

Robustness in harsh environments. How can we ensure that our grand ideas are robust in the real, and often harsh, environments that we work in? Deploying things in the ocean is often much harder and more expensive than designing them in the lab or office.

Trends towards low vs high tech. Low tech can be deployed in more places by more people more regularly. The democratisation of ocean observing is also an aim of the UN Decade. High tech solutions will have better capability and potentially higher quality data outputs. What is the 'right' approach?

Cubesat analogies. Can we learn from the cubesat system? This approach enables a bespoke science payload with a standard delivery system. It would require communication and agreement between instrument/platform manufacturers to develop and agree common interfaces.

What might some of the future implications be for what it means to be a marine scientist?

What potential equality, equity, inclusivity and diversity issues could arise?

Potential Positives

Broaden access to observational marine science. At present, the population of seagoing scientists is limited to individuals who are able to spend time at sea (up to 3 months according to RRS Sir David Attenborough plans). This requirement can be a barrier to entry to individuals with a disability or individuals with caring responsibilities. A shift towards more autonomous fieldwork would broaden access to observational marine science to a wider community. It could also create more choice for a seagoing individual during their career – so that during some stages of their career, they could participate in more seagoing, but at other stages have the opportunity to continue observation-based marine science without the requirement to go offshore. This broadening of access and choice could increase diversity of perspectives and of experience within the pool of marine scientists.

Reduced carbon footprint of individuals travelling to ships. Fewer ship-based expeditions, or expeditions with fewer individuals, would reduce the carbon footprint of travel to meet ships or return home.

Potential increase in data utility. Data may be more available to people from a wider set of backgrounds – subject to appropriate archiving – enabling greater usage of the data.

Potential Negatives

All-autonomous approaches will lose the human interaction with the environment. Is a future oceanographer simply a data scientist playing a computer game? Being on a ship during data collection can add a deeper understanding of the dataset and enable seemingly disparate connections to be made, particularly in multi-disciplinary approaches.

Reduction in hands-on training and working closely with the observations. A reduction in ship-based science could result in a disconnect between the observationalist and the observation, losing training and understanding of how a measurement is made and potentially resulting in a decreased quality of datasets. Some of this effect could be mitigated by appropriate training, capitalising on experience of seagoing scientists, or – in the case of glider piloting – greater involvement of the scientists in the piloting and early data quality control (QC) and real-time analysis.

Reduction in data quality with reduced scientist interaction with the observation. On site scientists improve the quality of data beyond current automated processes. It may be more difficult to ascertain when a sensor has gone wrong when it is 1000s km away. For the highest quality requirements (e.g., climate quality datasets), current options for remote calibration are insufficient.

Greater remote working reduces interaction with the community. Without the concentration of individuals at sea, there may be fewer opportunities for the spontaneous development of ideas and approaches. This could have negative impacts, particularly on multi-disciplinary science expeditions when individuals from a wide array of scientific backgrounds converge on a ship to spend days to weeks together. A shift towards autonomy would reduce this hidden benefit of collaborative working between people at sea.

Reduced recruitment potential of seagoing. The opportunity to go to sea can be a useful recruitment tool to bring in scientists and technicians. Without this opportunity, the practical aspects of a marine scientist as a data scientist may be less distinct from other data science careers.

Potential Shifts

Skillset change (science). With an increase in use of autonomous platforms and associated decrease in traditional ship-based observations, there will be a change in skillsets needed for marine scientists and technicians. There will be an increasing need for data science roles, for data archiving and interpreting large datasets. Change management will need to account for retraining and/or nurturing the next generation of marine scientists with an appropriate skillset. These changes will likely shift roles, providing increased opportunities for persons with skills to manipulate and analyse data from autonomous platforms and reduced opportunities for seagoing / ship-based science. In parallel, this skillset need may present new barriers around availability of expertise. Novel approaches and methods will require a high skill level in areas not necessarily present in the community of marine scientists. There will need to be the right pool of talent to pursue, implement and embed these new approaches in the field.

Skillset change (technician). On the technical side, the shift towards autonomy and robotics doesn't mean that no personnel are required (e.g., glider piloting, maintenance, etc). Staff will need to be able to operate the new technology.

Opportunities for collaboration

Links with social sciences**.** Working with social scientists will help to bring a focus on the long-term, and the importance of the oceans for communities in terms of resources, health (physical and mental) and infrastructure.

Links with industry and military. There could be advantages of collaborating with industry/military in terms of data collection efficiency (e.g., ships of opportunity, outsourcing) in addition to sharing of data, technology and approaches. Data from academia and industry should be integrated and made compatible.

Links with public and citizen science**.** Citizen science could help, not only to improve data collection and efficiency, but also to improve accessibility and positively shift the narrative of ocean science.

Internationalism. Whilst it is important to promote UK marine science and UK capability, we must also not lose sight of the advantages of collaborating internationally, not only in terms of achieving science goals but also for science diplomacy.

Key Challenges – Risk Management and Transition

What are the carbon footprint implications of the methodologies? Would the science be able to be done under Net Zero restrictions?

Carbon Cost: How do we compute it?

Point-of-use or all stages*.* If the definition considers all stages—manufacturing manufacturing, operating and end-of-life disposal—then the balance might change. Even autonomous platforms (e.g., gliders and Argo floats)—currently considered low carbon footprint—might have higher carbon costs when considering shipping, importing batteries, and discarding single-use batteries or the platform itself.

Alternative fuels to reduce ships' footprints. The definition of 'net zero' or low carbon was not fully determined at the time of the workshop. Some of the proposed solutions and their relative impacts on a 'net zero' approach will depend on how the carbon footprint of oceanographic observations is measured. Is the focus primarily on net zero at the point of use? In this case, further investigations would be needed to determine whether simply replacing ship's fuel by greener alternatives (e.g., green hydrogen, ammonia, sulphur or new fuel cell technologies) would enable ships to operate as they currently do, and/or whether new fuel types would restrict geographic coverage based on where refuelling can occur. More radical options like nuclear power and/or sailing ships might also be an option.

Ships are not the only carbon cost of marine science. It was also noted that many approaches to marine science may have carbon costs that are less visible than the fuel used on ships. What is the carbon footprint of satellites? Of server farms for numerical modelling or cloud-based computing? How can the carbon footprint be meaningfully normalised between different data types. If carbon offsetting can be considered, then can we also count the blue carbon from coastlines that are protected and monitored to offset the footprint of research work?

Maximising value while minimising harm

Marine litter may increase with reliance on autonomous platforms. While the focus of the project and the workshop was on net zero carbon, several questions were raised as to pollution and litter of possible net zero approaches. Low cost sensor platforms replacing ships may represent marine litter if they are not recovered (likely by ships). Battery-powered platforms will have an environmental cost associated with rare metals needed to manufacture.

Strategies to reduce carbon

Regional approaches reduce carbon. Rather than multiple countries maintaining multiple global class research vessels that cross vast distances between research sites, a marine station or regional surveys would reduce carbon cost. This hub-style approach could be applied either to research vessels or to localised experiments, where stationary (or mobile) charging hubs for drones enable continuous sampling and better temporal and spatial coverage. A regional approach would also reduce the carbon cost of travel to and from remote sites, which could be further supported by higher bandwidth connections. High bandwidth connections would enable remote specialists to instruct local generalists on methods.

Increasing efficiency of research cruises. At present, our use of ships may not be fully optimised. When a global class research cruise is undertaken, we need to use them as efficiently as possible (i.e., taking as many measurements as possible). Now extinct funding mechanisms (NERC small grants) used to enable PIs to add science to cruises that were already programmed; designating a regional approach with a global class ship (e.g., in 2025 the RRS Discovery will be in the Indian Ocean) would enable more efficient use of the ships by increasing science time relative to passage time. This would be analogous to NASA's approach to decide a destination for a probe (e.g., Titan vs Europa) and then invite proposals for that destination.

Science disciplines at risk with an autonomous approach

Science requiring heavy infrastructure may not be possible. Remotely operated vehicles (ROVs), seismics, deep sea drilling and mooring servicing would be a challenge without large ships.

Science requiring specific measurements may not be possible (see also "parameter coverage" below). Measurements for which there are no sensors cannot yet be done with AUVs, including e.g., a large portion of biogeochemical measurements, chlorinated hydrocarbons, sediment pore analysis, biological analysis, morphological analysis of sediment trap samples, trace iron speciation, radio isotopes. For some of these data types, the "customer base" may be small, in which case sensor development would not be cost effective. Additionally, though autonomous platforms may be developed to the point where samples can be returned to the lab for later analysis, some sample types will degrade enroute.

Science requiring manipulation of the environment may not be possible. Data that require manipulation of the environment (rates, processes, mesocosms) are unlikely to be possible without ships.

***Science requiring high levels of accuracy may not be possible*.** Calibration and maintaining data quality to the required standard for, e.g., climate studies, may not be possible with autonomous approaches. At present, ships provide a critical reference point for autonomous platforms (e.g., Argo floats).

Funding

Funding model to cover carbon cost. If a lifecycle approach is used to determine the carbon cost of a datum, who is responsible? Should the costs of disposal/recycling be included in research proposals?

Funding model for autonomy. At present some autonomous costs devolve to the project. A new funding model might be needed with central support for autonomous costs, analogous to the central support for ship operation.

Funding prioritisation. Is it more important to develop new technology or to develop existing networks (e.g., Argo)? Once a network is in place, how is further development incentivised?

Funding during the transition period. In order to build confidence in new methods, old and new technology must be run in parallel to determine how the measurement method impacts long term datasets. This transition period is necessary to understand data limitations and artefacts due to the collection platform. Additionally, is there a risk that while bringing in new technology, even newer technology overtakes it quickly?

Funding to improve carbon efficiency of current capability. At present, standard grant sizes do not allow funds for as many personnel as there are berths on a ship. As a consequence, ships usually go to sea with a large amount of space under-utilised. A structural change in funding ship-time research would require a mechanism for more 'bolt-on' projects to make a more efficient use of the ship. Additionally or alternatively, a new communication link between groups planning expeditions and the rest of the world could enable more 'piggy-backing' on an expedition. Those other groups could then identify useful additional observations to make to add value at minimal additional expense.

What are the possible challenges relating to temporal resolution or variability?

Challenge - Marine science sampling spans a large dynamic range. Depending on the application, the required dataset may span a large dynamic range in space and time. Some applications require very rapid sampling over a short duration (e.g., storms, extremes, seismicity, small-scale processes), while others require decadal timescale measurements spanning ocean basins (e.g., anthropogenic change). For the deep ocean and long timescales, there is not presently a substitute for ships. Long term time series would require cross calibration between old and new methods, and a change in data collection methods could impact the continuity of the data sets. This will inevitably pose a challenge to autonomous measurement approaches.

Opportunity – Adaptive sampling to respond to the environment. Power limitations may produce gaps in coverage or resolution of sampling. Adaptive sampling strategies could mitigate against these gaps. One could envision scenarios where platforms are parked on the seabed and ‘wake’ in response to interesting signals in the data, switching between infrequent to more frequent sampling regimes. This would require that autonomous systems are aware of their location which is not currently possible in all marine environments (sub-surface or under-ice).

Opportunity – Swarms of platforms to increase resolution. Using a large number of low cost platforms could enable higher resolution measurements through the use of ‘swarms’ with a host platform. However, controlling a large mixed fleet poses a challenge.

***Challenge - Reliability of platforms**.* Marine observations are made in challenging environments. Maintaining high quality data in harsh environments will require reliability in platforms and sensors which is not currently achievable.

Challenge – Measurements at interfaces are challenging. The interfaces between the ocean and atmosphere, ice and sea or coastal and open ocean areas are challenging. Technology that might be appropriate for one environment (e.g., Argo in the deep ocean) may not readily be used in another (coastal regions).

Opportunity – Autonomous platforms can go where ships can’t. A move towards more remote sensing/robots may enable greater coverage of the oceans including areas that are difficult to access using ships (e.g., near-shore features, areas with security/privacy concerns, under-ice). The Southern Ocean winter and Arctic ice season are two areas which are undersampled but could be more accessible to autonomous platforms than to ships.

Parameter coverage

Challenge – Sensor limitations. At present, only a small subset of essential ocean variables (EOVs) can be reliably measured to the required degree of accuracy by sensors deployed on autonomous platforms. Limitations include: biological sampling, eDNA genomics, rate processes (primary & secondary production, respiration), identification of marine life with different techniques in the water column vs the seabed.

***Opportunity – in situ measurements instead of bringing samples to the surface**.* Some oceanographic measurements (e.g., environmental DNA, respiration rates) require samples to be brought to the surface and out of their natural environment prior to measurement/analysis. It would be useful to be able to measure these *in situ*.

Challenge – Calibration and data quality. A move towards autonomous approaches presents challenges to sensor calibration and maintaining data quality to the required standard.

What are the possible challenges relating to data collection, processing and storage?

Challenge – Dealing with the data explosion. Expected data output rate will increase dramatically, and there is a need for a scalable solution for the expected (and unexpected) data types. Evolution of data science will be key.

Maximising data value not just quantity

With increased moves towards autonomy, the volume of data returned will increase.

Challenge – Data curation. Generating meta data for samples needs to be done well, and will require expertise in enabling/supporting the data pathway to match the deployment requirements. At present, data curation is not perceived to be important and thus is not prioritised. In addition, it will be important to also build in discoverability to new datasets to make them readable for AI and machine learning.

Challenge – Data access. Effort needs to be put into creating better access to data. How do you make high volume data accessible? At present, even existing data can be challenging to access with a lack of a universal and international data portal. Data archiving should be FAIR (findable, accessible, interoperable and reusable). Data from different sources (e.g., the Ministry of Defence or industry) may have other restriction to data access which could be considered.

***Challenge – Data quality control and quality assurance*.** Handling quality control and quality assurance (QA) for vast amounts of data generated by some platforms / approaches will need funding and staffing. This may also create opportunities for AI / machine-learning.

***Challenge – Long term calibration and validation of new sensors*.** New technology needs to be validated so the community can understand how data produced using the new method compares to data collected using historical methods. In order to support sensor development, we need to decide how accurate the sensors need to be.

Opportunity – AI and machine learning for data ingestion. The larger volumes of data may create opportunities for machine learning to process data where at present a scientist's intuition/understanding needs to fill sampling gaps.

Opportunity – Generation of new best practices.

Bandwidth from platforms and ships

Enabling dynamic decisions on sampling. There is high demand for more observations with real-time data access to make dynamic decisions on sampling rates. This would improve the knowledge gains from observations with finite limits (e.g., sensor lifetime, number of samples, short lifetime of target phenomena).

Enabling a shore-side team to complement the at-sea team. High bandwidth data rates to ships would allow data transfer from ship-to-shore for a shore team to help analyse data and make real-time decisions. This would maximise science output with reduced time commitment for sea-going scientists and enable collaborations with shore-based scientists allowing more science for the same ship-time investment. Scientists on the ship could maximise effort on *in situ* data collection of samples needed to calibrate sensors or do the actual science (e.g. for biological sampling of organisms).

Challenge – broadband would need to be more reliable. To enable reliance on ship-to-shore data transfer and real-time decision-making, the ship's broadband would need to be both faster and more reliable. This would likely require broadband redundancy. Otherwise, the shore-connection could not be relied on.

Appendix 4: Full survey report

Introduction

The Net Zero Oceanographic Capability (NZOC) project is a NERC scoping project to identify areas in marine seagoing science that require further development, to enable NERC to meet its carbon goals in the future. Seagoing science can be particularly carbon intensive, so with this survey we are exploring opportunities and challenges to moving towards a sustainable research infrastructure that maintains and enhances the UK's world-leading position in oceanographic research and meets the needs of the scientific community.

In this survey, we asked about how new technology is being used in research and whether there are barriers that have limited uptake of new technology. We also asked about views of the future technology that will be coming available, or could be developed, in the near term (2020-2035). We requested views from those in primary marine research and any stakeholder or end-user of marine or oceanographic data.

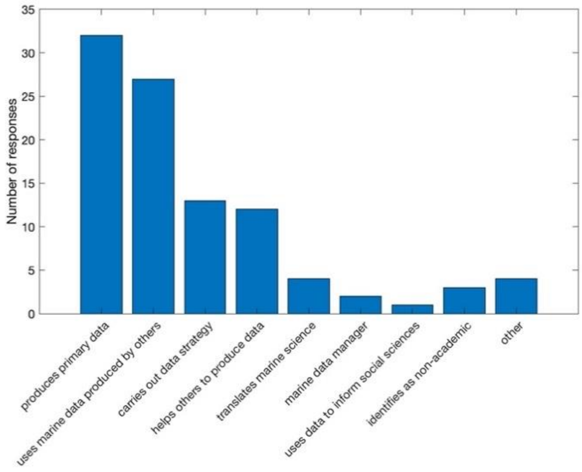
For some disciplines, there are substantial barriers towards moving to a low carbon approach, either due to the space-time scales of observations required, the parameters that need to be measured, or the locations of sampling (e.g., deep sea drilling). Our aim was to identify both the opportunities for new technologies to transform marine research, but also the challenges that exist and – where appropriate – to consider whether some of those challenges or barriers can be ameliorated through further technological developments.

In total there were 44 respondents (6 in trial, 38 in main survey – combined here in this report).

Results

Use of marine data

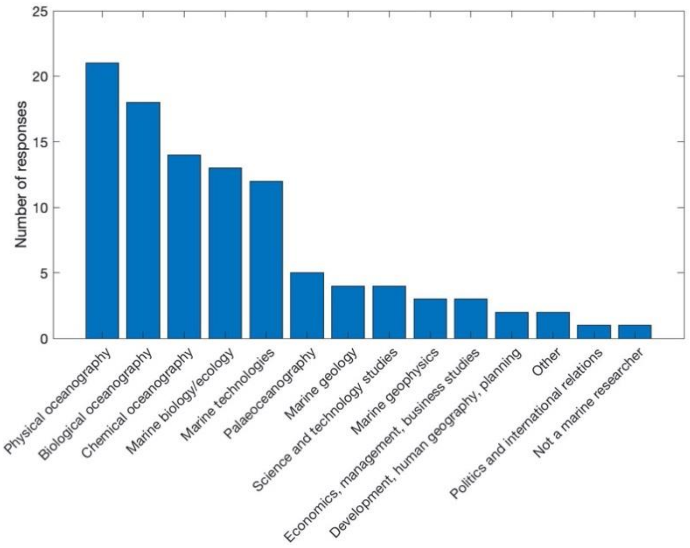
- 73% identify as being marine researchers who produce primary data
- 61% identify as being marine researchers who use data produced by others
- 30% identify as being marine researchers who work strategically to consider what data need to be collected
- 27% identify as being marine researchers who help others to produce data



Focus of research

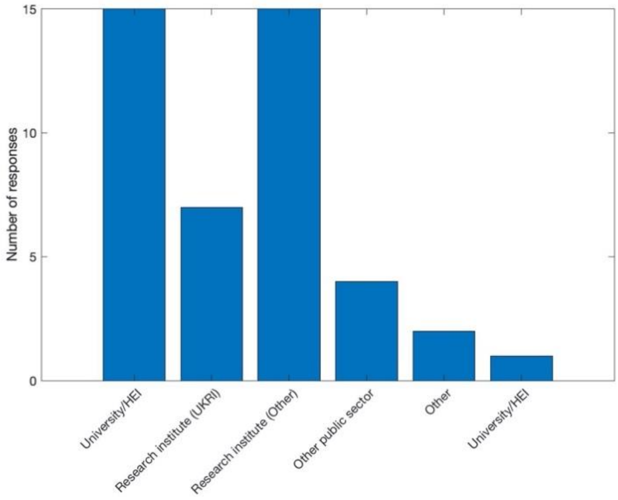
Majority natural sciences

- 48% Physical oceanography
- 41% Biological oceanography
- 32% Chemical oceanography
- 30% Marine biology/ecology
- 27% Marine technologies and engineering



Work sector

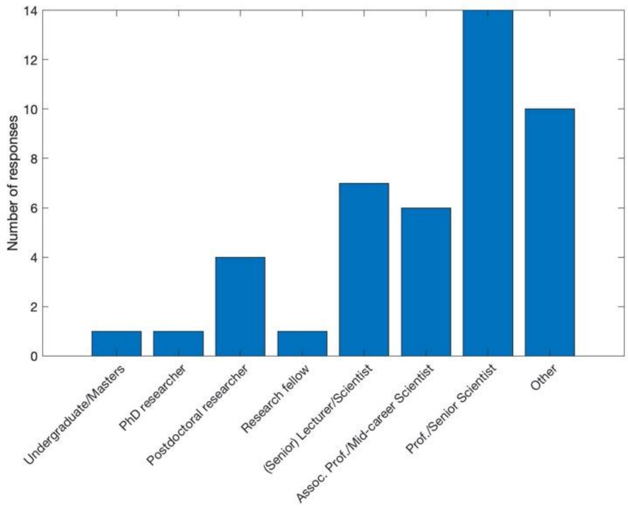
- 34% Research Institute (non UKRI)
- 16% Research Institute (UKRI)
- 34% University/HEI
- 9% Industry
- 5% Other public sector/civil service



Career stage

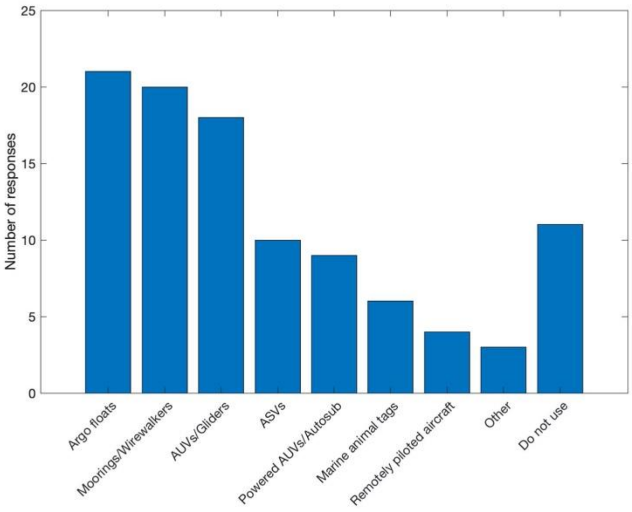
Mostly senior, with few ECRs

- 32% Professor/Senior Scientist
- 14% Reader/Associate Professor/Mid-career
- 16% Lecturer/Senior Lecturer/Scientist
- 23% “other” (Additional selected categories: technician, private sector, retired)



Current use of autonomous platforms or marine animal tags

- 48% Use Argo floats
- 45% Use Moorings/wirewalkers
- 41% Use Autonomous underwater vehicles
- 23% Use Autonomous surface vehicles
- (“others” include Earth-observing satellites, sediment traps, ocean bottom seismometers, benthic landers)
- 25% Do not use autonomous platforms

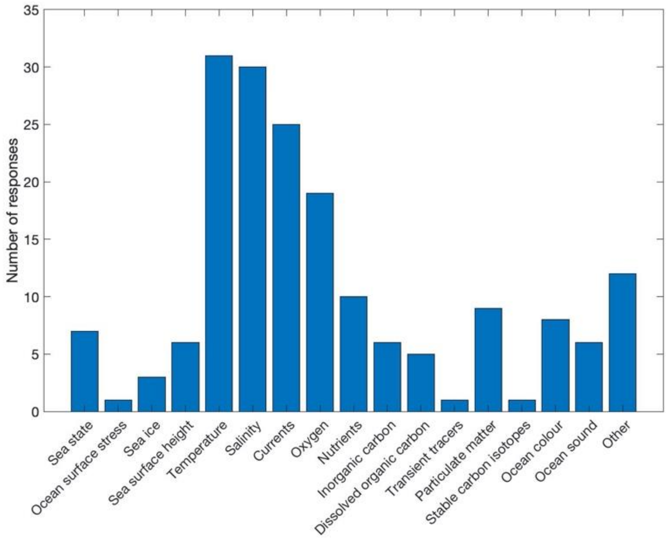


Current EOVs from autonomous platforms (from those answering yes to using platforms)

- 70% Temperature
- 68% Salinity
- 57% Currents
- 43% Oxygen

All but one of the other EOVs (Nitrous oxide) were selected.

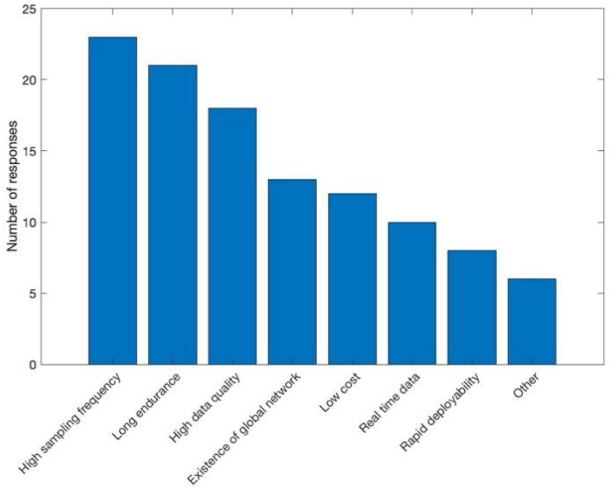
Others: pH, zooplankton biomass (acoustics), fish abundance (acoustics), seafloor images, turbulence, multibeam bathymetry, Eh, microbes, benthic organisms



What are the important advantages of the platforms used?

All options selected, but most important options were:

- 52% High sampling frequency/resolution
- 48% Long endurance
- 41% High quality data



Others: Public availability, under ice sampling, opportunistic sampling,

"In terms of ocean obs, our platforms use animals to extend the reach and compliment other obs approaches in data poor areas where animals spend time"

What are the barriers to using autonomous platforms?

All options selected, but most important options were:

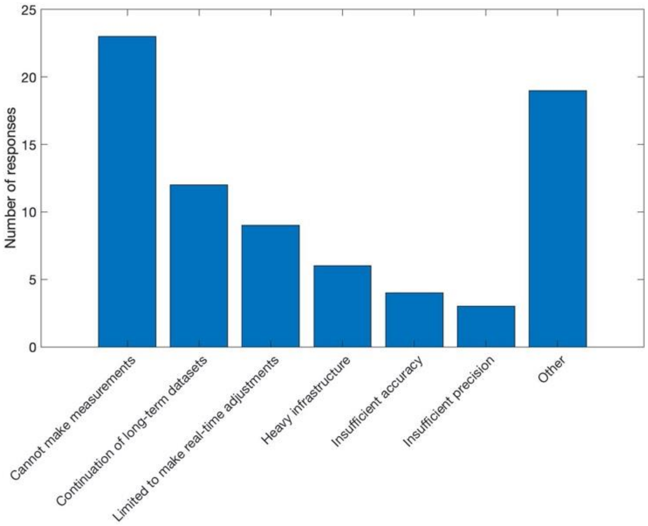
- 52% Cannot make autonomous measurements (e.g., sediment coring)
- 27% Continuation of existing long-term datasets

43% selected "other" including cost, confidence, data security, access, scalability and platform range

"poor reliability/confidence or means to ascertain correct procedure has been carried out"

"access to technology in the first place; feels like guarded territory"

"Depth rating and locational precision for deep water outflows"



Main themes:

Challenging sampling (e.g., biology, but also the case for chemistry)

- continuous feedback required

- risk of contamination

- collection and/or in situ incubation of organisms

- rates of biological processes difficult to measure

- species identification

"*With biological parameters such as water sampling for plankton, it is essential to have a feedback to know for example if the correct number of litres have been filtered to obtain the sample. Also, things like sample contamination through leaky value etc are hard to have a feedback for, making certainty in the autonomous method not 100%. Collecting physical samples of zooplankton and micro-nekton is limited by space/means to store sample. In situ incubations of larger animals require capture of that animal which is not trivial for an autonomous platform.*"

"*The microbiology focus of my work often requires flux measurements and experimental manipulation. Autonomous systems exist for this but they aren't great.*"

"The nature of the benthic boundary layer (unstable/muddy) will present fundamental problems to deployment and autonomy (in contrast to, for example, the Mars rovers that roll over dry surfaces)."

Access

- safe access to seafloor

- safe access to under ice/polar regions

"*Autonomous platforms currently stay clear of the seafloor, which is my main area of research.*"

"*…my research is principally based in the deep sea and/ or Polar Regions where access is challenging as is the durability of kit.*"

Large payload sampling/geophysics

"*On the geophysical side, sub-bottom profiling (chirp-type) might be feasible. Magnetics and gravity would be nice, but are both more technically challenging, and in the case of gravity, particularly expensive.*"

"*not able to sample water for further analysis (e.g stable isotope analysis)*"

Cost

"Autonomous system generally require major research grant support. My work and funding generally do not enable me to access/afford the extensive costs and support that most forms of autonomous systems currently imply."

"New sensors are not necessarily the issue, it is the ability to deploy them for useful periods of time without the need for a major grant (which are increasingly difficult to win) to cover the support required, never mind having any resources left to do some science and write some publications with the results."

Data quality

“Autonomous systems offer diverse levels of accuracy, data collections are piecemeal and sporadic, quality is poorly known, finding out what data exist is difficult, new deployments require specialist staff and equipment and are expensive.”

Inherent understanding of systems, and nature of skillsets

“There is an inherent understanding that you learn about the systems when you see and experience them first hand. We need to consider that too when moving to the more virtual world.”

“two sets of technologies - autonomous and human-directed - are appropriate for different stages in the research process, and complementary in that regard; autonomy cannot provide a solution to all needs.”

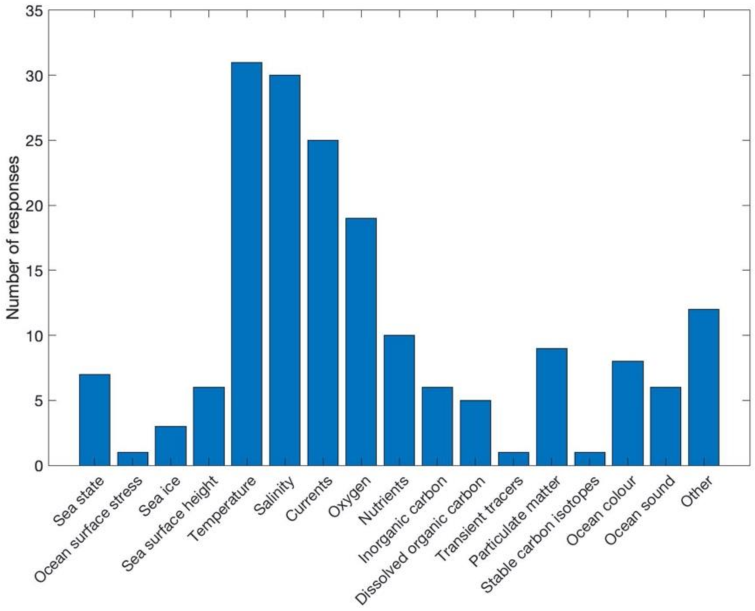
“Currently not feasible to concurrently measure multiple biological and biogeochemical rates, as we can on a multidisciplinary cruise. I don't see automation much impact on this assessment in the next 15 years.

And what would be the point of an automated vessel with remote participation when most of our experiments need to be done in labs on the ship? Also, if Covid has taught us anything, it's that video calls are no substitute for the creative bouncing-of-ideas that happens in person, particularly on cruises.”

Sensors and EOVs

- 34% Temperature
- 36% Salinity
- 25% Oxygen
- But also 23% other (i.e., not covered by GOOS EOVs)
- 0% Transient tracers, Nitrous oxide, stable carbon isotopes

Others: Turbulence, echosounder, zooplankton biomass (acoustics), fish abundance (acoustics), benthic biology



Is new sensor data collected with good automation and to a high standard?

Mixed response, with most people (56% of those who answered this question, and 34% of all survey respondents) answering "some yes, some no"

Main themes:

Funding and scope for innovation and commercialisation

"Major challenge is commercialisation paths from research, and funding to overcome valley of death for new innovations. See https://nerc.ukri.org/innovation/activities/energy/oilandgasprog/ipog-review-public/ for further information on a number of the challenges related to NERC funded innovation."

"There is room for closer work between the sensor development teams and researchers who could make use of data from test deployments, and for researchers to get earlier use of some sensors as they are developed."

"In my experience we would need more time, more funding and hence more data to create a proper validation/transition dataset. Also when dealing with new technologies the deployment and manufacturing times are so long that is often too hard to create a proper set up in the time frame of a given project."

"Experience with Argo shows that there is a non-trivial path to go from a sensor which can be deployed, to a sensor which is fit to deliver science-ready data on an enduring basis across a large fleet. With this in-mind, Argo has introduced a framework for entering Argo, see: https://argo.ucsd.edu/expansion/framework-for-entering-argo/"

"Extension of current successful collaborative R&D project with Southampton University, which needs extending to NOC and MOD with necessary funding."

"For the Royal Navy there are plenty of solutions to our data collection requirements, the difficulty is seeking funding and SQEP to procure and maintain our own systems"

Data quality, calibration, and processing

"The complex biological data (zooplankton, fish and above) - frequently the data sets are too large for transmiting back. The algorithms for converting the raw data to measurements of zooplankton and fish for example require greater complexity of the acoustic instrument, which in turn requires power, which in turn limits the platforms it can be on. I would suggest that acoustics (active and passive) remain current challenges in terms of power, memory, communications (Bandwidth for sending data back) and interpretation (e.g. AI etc)"

"most sensors (e.g. oxygen, H2S) still need re-calibration with conventional methods"

"My experience is with new spaceborne technology. The quality of the new technology data depend on the availability of proper calibration/validation initiatives and in situ fiducial data infrastructure, which exist for some but not all new spaceborne sensors."

Sensor failure

"We tried new carbon and pH sensors but both failed. They were highly pressure dependent although the manuals claim other wise and we couldn't use any of the data."

"Instrument failures still occur during long deployments-some likely caused by natural phenomena such as earthquakes and some due to hardware failures. There is still a lot of work to do in the field of ocean bottom seismic deployments."

If you don't use new sensors, why not?

Main themes:

Not relevant for field of expertise

"Don't know of a sensor to replace sediment traps"

Sensors not available at the moment measuring the variables required

"Not currently sensors that would measure the variables I require. Nutrients could be useful, but needs to be enough justification for them to go on a mooring, and funding to be found for this. Would be good if there is a review of for example, nutrient sensors currently available, so those not in the sensor development field, are aware of what status the development has got to, which sensors can be relied upon for use on long term moorings etc."

"There are still limitations in chemical sensors, and again, none of them currently cross the sediment-water interface."

"Cannot measure biological rates with current sensors (e.g. zooplankton grazing, phytoplankton nutrient uptake rates)"

Accessibility

"These types of technology are not typically used for the purpose of collecting "physical" samples. In addition, durability of kit tends to fall short in places like the deep ocean and Polar Regions."

Also, information accessibility:

"With regards to new in situ sensors, it is difficult to know how to get started as the information is difficult to find."

Costs

"It is not the vessel bandwidth that is the issue, it is the scale of the costs involved that can be supported by anything other than major UKRI research grants. UKRI funded research represents one small part of the totality of marine observations that either currently takes place or are needed. Consider the number of marine consultancy companies conducting operations every day and their continual drive for cost effectiveness."

Commercialisation challenges

"In the commercial realm, the contractual arrangements often put technology risks on contractors, therefore conservatism in new technology deployment offers the path to lower perceived commercial risk. This is particularly true where environmental permitting is concerned as the risk of delays in licensing for the end client may be significant. There is also perhaps an unwillingness to engage end clients and regulators in the validation of technology. End-clients in operation departments are

inherently conservative, even if the technology may offer cost savings and/or improved data quality. Regulators are perhaps less willing to engage due to resource issues."

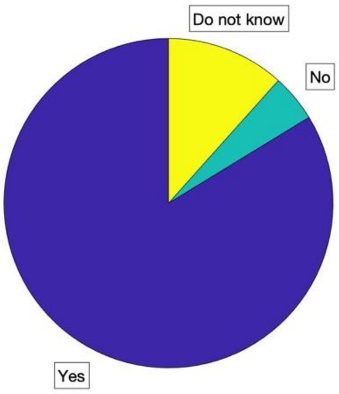
"Why fix what isn't broken?"

"Probably a lack of willingness to try things that may fail - at present it is more convenient for me to stick to the tried and tested technology."

Future projections

Do you anticipate using new sensors/platforms over the next 15 years?

The majority said yes (84% of those who answered the question, 82% of all survey respondents)



What technology would change your field for the better over the next 15 years?

75% New Platforms

57% New Sensors

57% Increased bandwidth

Main themes:

Autonomous sailing ships

"Fully autonomous surface vehicles for long duration surface flux measurements (and ideally profiling for depths >mixed layer)"

Under ice/polar capability

Under ice capability would be a great asset, particularly with regard to collecting data over the winter in the Southern Ocean, for which data are limited.

Seafloor/deep sea capability

"Autonomously moving benthic lander systems that can measure benthic fluxes, benthic boundary layer processes, potentially take discrete samples and store them."

"Trawl resistant mooring mounts"

Coastal area capability

Sensors for biogeochemistry and biology

"Sensors to measure biological variables such as phytoplankton abundance and community composition, as well as biogeochemical variables such as particulate organic carbon flux"

"Platforms that can measure multiple biological rates simultaneously on large time and space scales (this is more like 150 years away, than 15)."

"eDNA on board sensor - bacteria/phytoplankton/zooplankton onboard sampling"

"Greater in situ (and possibly even real-time) sensors for parameters that characterise the geochemical environment, e.g. dissolved constituents relevant to microbial processes"

"All and anything needed to address key carbon questions."

Multi-sensor platforms

"Sensors that enable continuous monitoring and regular (doesn't necessarily need to be real-time) feed to shore, but also platforms that can support multi-sensors with a high confidence in their outputs"

Extended deployment technologies/efficiency improvements, with an eye on marine litter

"Extended deployment technologies with data telemetry and system redundancy for longer deployments between service cruises. Full instrument suite telemetry with accessible open source archiving to limit redundant cruises"

"simple, low-cost, carbon-free intelligent platforms that can be easily assemble and operated in third-world countries to provide a constant flow of oceanographic data from remote and isolated areas."

"Gliders that are powerful enough to measure a basin section like OSNAP, RAPID etc. would be great with the ability to observe similar water column data you can do during a cruise."

"Autonomous power harvesting systems with telemetry onto which a range of sensors can be applied. These are needed to operate in all sorts of remote and difficult locations."

"Low-cost disposable autonomous long-endurance self-calibrating drifters that measure sea level, sea state, ocean current vectors, surface temperature and salinity profiles."

Onboard processing/adaptive sampling/ship-to-shore communications/telemetry

"On-board processing could permit improved adaptive sampling. Adaptive sampling was quite fashionable when power/memory were significant barriers to extensive data collection. However, for a number of high frequency processes, e.g. passage of internal waves, having the ability to identify a wave form to increase sampling would greatly improve endurance and data quality. Similarly if the data collected could be processed to provide appropriate information to transmit it would allow for improved subsea data to surface to satellite comms for informing real time decision making. See https://nerc.ukri.org/innovation/activities/energy/oilandgasprog/nanopam-next-generation-acoustic-monitoring/ as an example. If those comms could be improved it would also provide data security and timeliness."

"Being able to hook up to ongoing research from shore would be great for being actively involved in the work whilst potentially not being able to participate in long expeditions due to teaching and caring responsibility. Since my practical work is mostly laboratory based it can be done onshore, but having a say/insight into the oceanographic variables being recorded and how samples are taken would be very helpful."

"Gliders with greater autonomy, with higher level instructions and more onboard decision making, for under ice and reducing time needed for piloting (and more autonomous onshore sampling)"

"Real time mooring data"

"It would be great if we could recover data in real time in some instances for example after an earthquakes or for geodetic purposes. Bandwidth and telemetry would be key. Also I think acoustic GPS is coming online and will be an important addition to capability, which also needs good water column data to be successful."

Are there additional EOVs that you would like to measure/monitor using new (or improved) platforms/sensors?

Main themes:

Inorganic carbon parameters

Particulates (concentrations, fluxes, sinking rates, size distributions)

"Particulate organic carbon flux - there is work looking at optical approaches, but many autonomous methods get at particle concentration, and still require assumptions of sinking speed. Then we could get a much better idea of ocean carbon uptake through the biological carbon pump, as we would not

be relying on spot measurements, and could increase the spatial and temporal resolution of sampling to try and more accurately quantify and balance the budgets."

Benthic fluxes (carbon, nutrients, metals)

Biological parameters e.g., Viruses and bacteria, productivity, species

"Your list of EOVs completely misses the Biological and Ecosystem EOVs https://www.goosocean.org/index.php?option=com_content&view=article&id=170&Itemid=114"

"Basically all the biological variables. Those for plankton imaging and benthic animal imaging are getting better. We're aiming to develop lower cost molecular (for microbes and eDNA) sensors."

Integrated transports

Pollutants

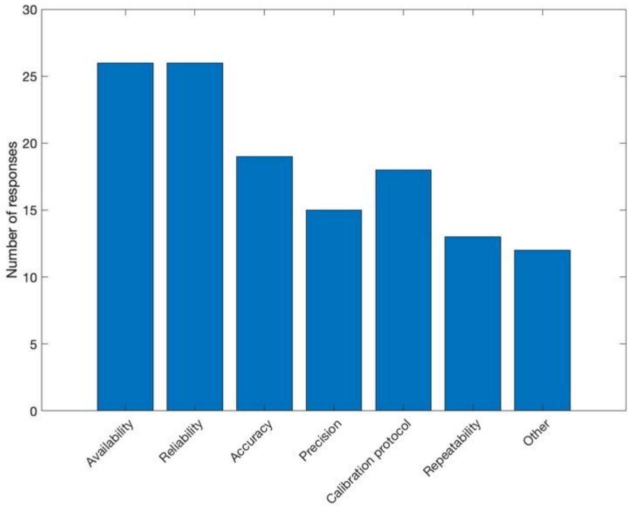
Geophysics e.g., gravity, magnetics, bottom pressure

What would it take to get these sensors into more widespread use over the next 15 years?

All answers selected, but the most important were:

- 59% Availability or ease of access
- 59% Reliability
- 43% Accuracy (34% Precision)
- 41% Calibration protocol

Others: Power, data collection duration, economic total life-cost, democratisation of access, longevity, use of Certified Reference Material, training for users



Based on your observational needs, and the current available technology, where are the gaps in space-time measurement of your key EOVs?

- 66% Large-scale coverage
- 52% High spatial resolution
- 34% High frequency
- 20% Low frequency
- 20% Other: Seasonal coverage, power, long time-series, targeted locations, capability for studying in sediments

Additional useful comments:

"I am hopeful that optical methods will continue to improve, which also requires image processing software to extract things like sinking speed and particle composition. Image analysis is tricky in terms of particle classification, and does not allow for accompanying variables like Si, POC, PIC content of those particles without some kind of 'average' particle calibration. I guess there is a balance between what we can obtain from physical samples and what we can get autonomously, and I would hope that a mixture of the two might be the way to go. That way we can still up the spatial and temporal resolution, but still be able to take a detailed look at particles to understand the mechanisms at play, not just quantify the budgets."

"The potential to move away from moorings to autonomy is very interesting, however it would be interesting to understand how to value frequent data at a single site versus low temporal resolution across an area, versus a combination of the two to gain a better understanding."

"Taking ocean heat waves as an important area that will grow with global warming. On the one hand it would be relatively simple to have a monitoring system to automatically identify the formation of a heat wave and a network of easy-to-use autonomous vehicles that could be deployed in the area from a local base, measuring temperature, salinity, oxygen etc. Issue is having the baseline data for the area before the heat wave trigger (especially in areas too shallow for Argo) - models or shelf-Argo/gliders would be needed on a large scale to be pre-emptive."

"In 2012 we tried to purchase an echosounder to put on a glider. Due to power limitations the only one we could get was single beam single frequency (similar standard to 1950s echosounders). Now, there are wideband splitbeam echosounders - but they test the power consumption of autonomous vehicles and produce volumous data that exceeds realistic iridium comms. Let alone the conversion (or calibration if you like) into usable metrics for EOV style analysis (where people could agree to a common amount)."

"There is a generic need to develop observational methods that reduce the operational burden and need for extensive staff time for installation, operation and maintenance and avoiding large marine assets for deployment and recovery where at all possible. How about autonomous deployment and recovery of moorings or sea bed frames? Try some thought experiments for how one might go about getting a particular instrument into a particular location/environment (and back) with the minimum vessel or carbon footprint."

"Moorings need to be seen as autonomous systems, as do SOOPs

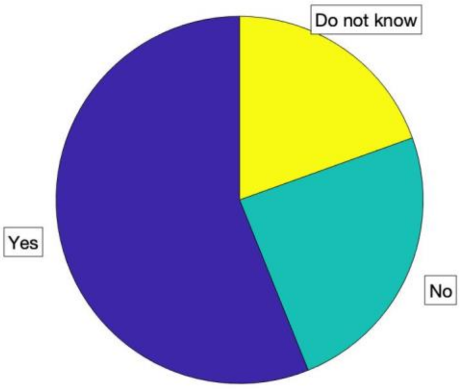
Other AUVs don't currently have enough variables measured (requires smaller sensors)"

“Many of the constraints acting on our animal borne instruments are difficult to avoid. I strive to find ways of stepping around them by making the instruments act as data collection agents that choose levels of sensor accuracy, resolution, frequency of sampling, data processing etc to minimize energy use and bandwidth. That is the tag's on-board processing acts to insure its resources of energy and bandwidth are tuned to structure the data that will be sent or stored the questions being asked”

“A main challenge within Argo is deploying floats into Southern Ocean were deployment opportunities are scarce. This is as much a coordination challenge as a technical one. We are looking at none traditional deployment opportunities, such as resupply ships, cruise ships and aircraft based deployments to overcome these challenges. We will still need research ships to support deployment of BGC Argo floats due for the need to undertaken CTDs on deployment for initial calibration purposes.”

If bandwidth on ships were not limited, would it change how you do science at sea?

The majority said yes (56% of those who answered the question, 52% of all survey respondents)



Main themes:

Potential to improve accessibility

“Remote participation would be a real option for people with family commitments, disabilities etc., and for that you need camera systems and good reliable internet.”

“High bandwidth could either make it easier for people not on board to work with the data, or reduce the inconvenience of being on the ship and so allow people to come who otherwise wouldn't.”

Improve interconnectivity of autonomous systems

“ Increased bandwidth would support sensor development and new temporal methods of analysis but also improve the interconnectivity of sensor platforms, self diagnostics, and adaptive coverage for sensor data breaks and dropouts. Higher bandwidth will enable full-ship scale autonomy”

Improve capacity of data acquisition and usage at sea

“needs extending to maximum as photographic data is certain to increase and will be gathered from deeper depths and in more remote areas”

“rather than band width per se, what would help at sea operation is ability to run model while at sea and generally get a systematic access to curated remotes sensing products easily and systematically. all of this is now possible, but must be arranged by each PI. This is ineffective as requires a lot of 'reinventing the wheel'”

“This applies to both ships and data transmitted from moorings, etc. LEO comms satellites should change things dramatically with respect to the amount of data that can be provided in near real time. From a commercial perspective this might allow offshore developments to move forward quicker and at lower cost as assumptions in design can be tested earlier in the development phase.”

IF unlimited - could get experts to set instruments up and QC whilst not on board, can ask for expertise when new things seen.

Improved visibility/outreach

“Better bandwidth would make working day to day so much more effective. This would also open up opportunities for the HE sector, providing students with a real time insight into life and work at sea. Better communication would also make the practicalities of working at sea more bearable and possible for all scientists.”

NB: Benefit of reduced bandwidth? Ability to focus at sea

“A benefit of reduced bandwidth is the focus on the work you are doing at sea - instead of trying to maintain your 'shore' job at the same time as intensive work offshore.”

“Overall I think the core of having a focused team on board aware of all the issues and spotting any issues as quickly as possible won't change significantly.”

Other useful comments:

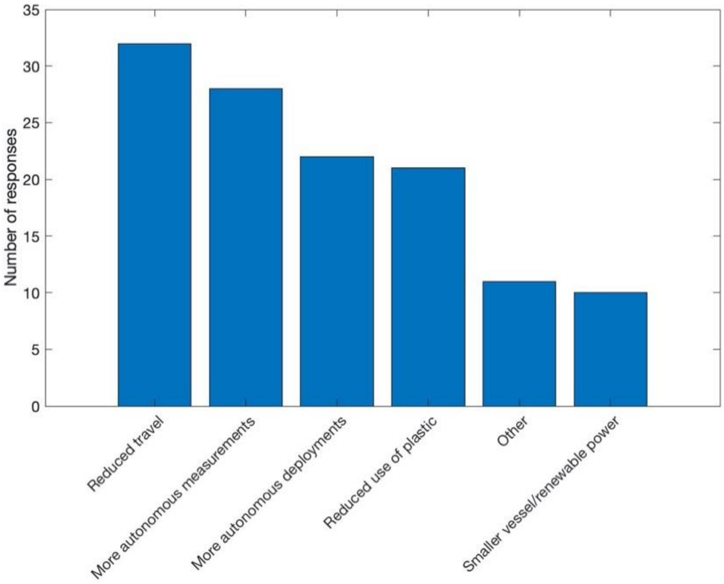
“The R/V Falkor (Schmidt Ocean Institute vessel) has been working off Australia for most of the last year due to covid-19, and I know they've had some chief scientists working remotely, rather than on the vessel. It might be worth seeking information from them.”

“The UK has lagged behind other nations in using telepresence for remote cruise participation; in my experience (as a PSO), increased bandwidth has been seen as a "luxury" for the crew to watch football, or for "nice to do" (but not essential) public engagement, rather than as a primary tool to widen access and participation, increasing research bang-for-buck.”

Where do you think that there are areas in your research where carbon can be reduced at point of use?

All options were selected, with the most important being:

- 73% Reduced travel
- 64% More autonomous measurements to replace ship-based measurements
- 50% More autonomous deployments per expedition
- 48% Reduced use of plastics



Others: Retaining the suite of vessel sizes but adding renewable power plants, replace single use systems with reusable tech, filling berths, maximize science of each cruise, longer cruises (less transit waste between short cruises), partnerships with institutes closer to point of departure for local participation, specially recruited roles, increased focus on coastal environments, carbon offsets

Other useful comments/suggestions [underlining added by editor]

"Survey transect work, ROV observations, and hydrography may be the best candidates for smaller footprint platforms."

"Each science mission involves lots of shipping. Shipping seawater is especially costly and wasteful. Modernizing and better controlling ship science labs could help reduce need for excessive shipping. Also, create a national seawater sample library. Lots of samples already exist, but most are in boxes, hidden/forgotten. Suggest create a national library of seawater samples (each cruise would take large samples -cubic meter + filter lots of water) in some representative locations. Water, particles, etc. are what most oceanographer want. Cruises not always needed if basic hypotheses could be tested from available 'sample library' (i.e. a bit like sediment cores in IODP)"

"… the deployment of autonomous solutions to replace moorings could offer significant scope to reduce ship emissions, particularly with respect to mob/demob to area of interest."

"while there is a technological aspect to reducing emissions in oceanography, there is also a need to change attitude and procedure vis-a-vis 'cruise ownership'. Most scientists on cruises are 'amateur',

learning on the fly, or with limited sea experience. Would be good to have professional cruise scientists (not 'just' technicians, but trained chemists, physicists, etc), doing cruises full time. These would be best placed to reduce carbon footprint, optimize protocols and advise visiting scientist of each cruise. i.e. in the same way as ship has a engineers, crew, there should be a science crew of scientists, with oversight on technicians."

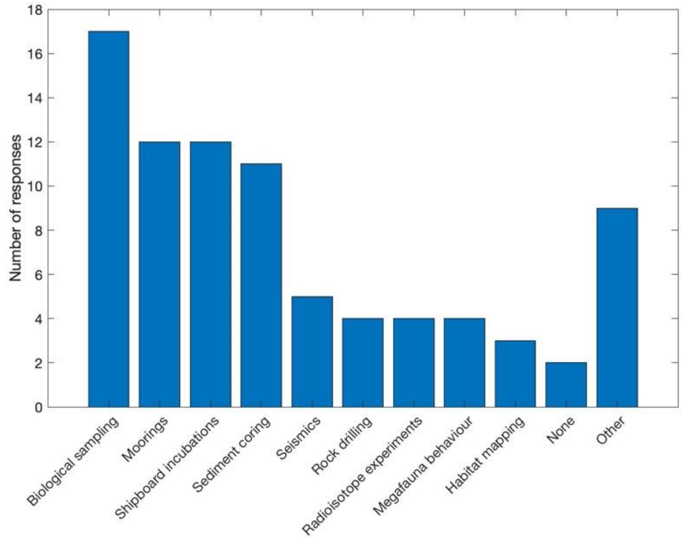
"Black Pearl https://en.wikipedia.org/wiki/Black_Pearl_(yacht). Can we use alternatives rather than replace ships?"

"We use a number of ways to minimize costs and energy in getting out to the field to attach tags and sample animals. We use small sailing yachts or ships of opportunity (tourist ships etc) when possible. If a conveyance is going where we need to go and we can tag along, extra energy and other costs can be minimal."

What measurements or methods in your field would be a particular challenge to move to a low carbon approach?

All options were selected, but the most important were:

- 39% Biological sampling
- 27% Moorings
- 27% Shipboard incubations
- 25% Sediment coring
- 20% other: offshore oceanography, biological rate experiments, most isotope analyses, satellite launch, all experimental work

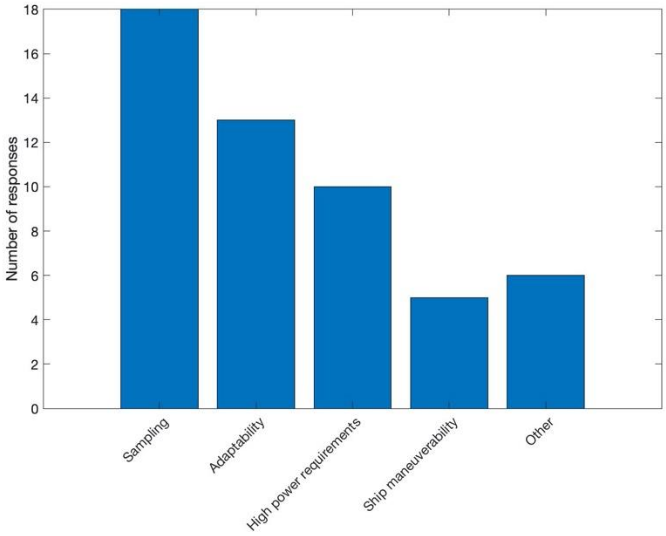


Are there other aspects of your fieldwork requirements that will present challenges to the net zero objective in 2035?

All options were selected, but the most important were:

- 41% Sampling
- 30% Adaptability

- 23% High power requirements



Other useful comments:

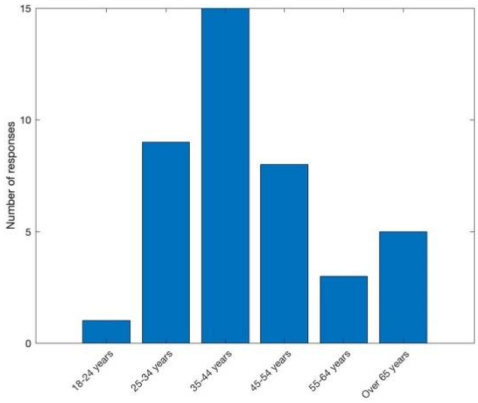
"I'd suggest the UK (and global) research community will need to maintain some global ocean capability if we want to keep doing some aspects of the science we currently undertake. So we will still need large global class ships. We may be able to get away with less of them"

"For moorings, it is the deployment and recovery of these moorings that is the problem. As long as there are still cruises going to the regions of the moorings then this process can be tacked on, to avoid a bespoke trip for mooring recovery (this i believe is rare). I think that moorings will improve in terms of the length of time they can be deployed for, and with telemetry data can be fed back. However, where ice bergs are a problem, there is no surface expression of the mooring, so telemetry is not yet possible. There is also the problem of physical samples, e.g. sediment trap samples, water samples, for which the data cannot be obtained without collection of the mooring. So longer deployment periods can lead to long gaps between data recovery (may be tricky for PhD/post doc time frames), and also increases the risk for data loss, for example, in a 2 year deployment period, if an instrument fails, then it would not be until recovery that this is found, and as many open ocean moorings are turned around on site, unless researchers have a duplicate set of all instruments/sensors (very costly), then it would be a further 2 years before the instrument could be replaced (so 4 years data loss). The risk of data loss therefore needs a lot of thought when determining the length of deployment of a mooring between servicing.

Incubations and biological sampling require the same collection of a physical sample. For bacteria and plankton, in situ incubation systems are more doable/are currently in use, as it requires trapping of a water parcel. however, for larger animals this is trickier. It would need the ability to detect and capture a particular fish/euphausiid species."

Diversity monitoring

Age (3 prefer not to say)



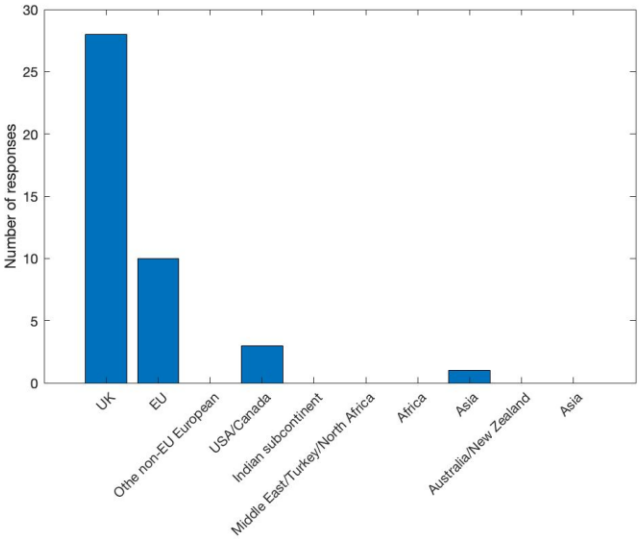
Gender

	# responses	%
Woman	24	55%
Man	16	36%
Non-binary	0	0%
prefer not to say	4	9%

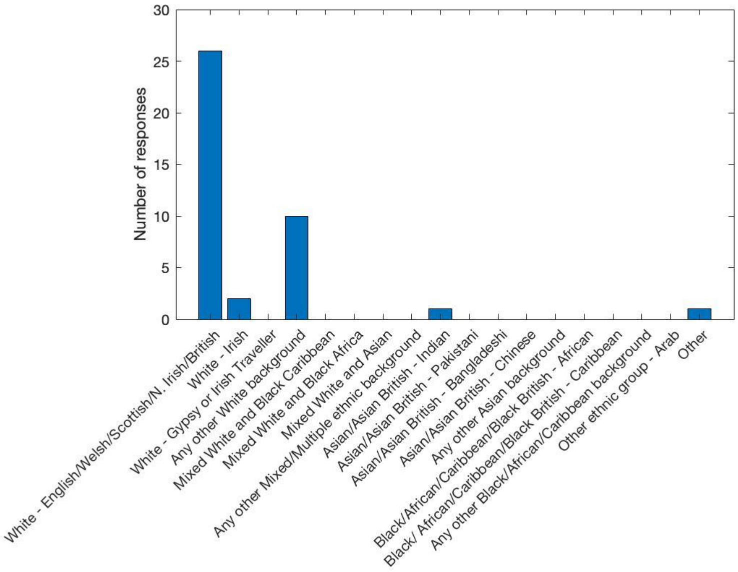
Same gender as birth?	# responses	%
Yes	39	89%
No	0	0%
prefer not to say	5	11%

Region

(2 prefer not to say)



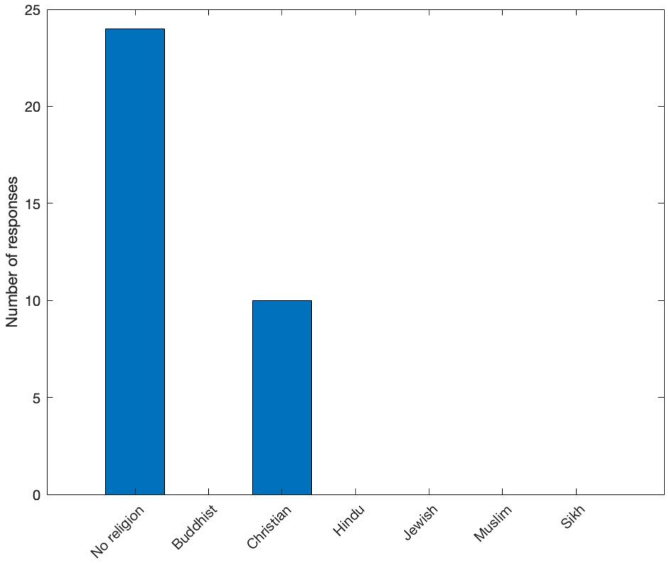
Ethnicity (4 prefer not to say)



Sexuality

	# responses	%
Bisexual	1	2%
Gay man	0	0%
Gay woman	0	0%
Heterosexual/Straight	36	82%
prefer not to say	7	16%

Religion (9 prefer not to say)



Appendix 5: Alignment with Broader UKRI Policy

Recommendation	Alignment with UKRI high-level priority[47]	Alignment with NERC objectives *and examples of long-term ambitions*[48]
Invest in an equitable, diverse and inclusive marine science community.	*"Only by recognising and nurturing everyone and introducing diversity into the way we interact can we enrich our lives as creators of knowledge. We can then better understand the world around us and be empowered to tackle the many challenges we face as individuals and as communities, nationally and globally."*[49]	
Form a working group to identify priority development areas for marine science observing. **Engage with international stakeholders, especially those involved in GOOS to ensure consonance where appropriate.**	Driving transdisciplinary international research collaborations Supporting global collaboration and connecting to global decisions	Global environment *"Continue to invest in research and innovation that addresses global issues through internationally coordinated science, brings UK expertise in environmental science to bear to global challenges, takes on challenges in developing nations and responds rapidly to environmental emergencies"*
Develop data skills training programmes for all marine scientists. **Ensure that there the sufficient trained specialists in place for an effective future data ecosystem from the start.**	Promoting technical skills Enabling early career researchers to bring fresh ideas	Best environment for research and innovation *"Create new communities and nurture a new generation of researchers who take whole-systems approaches as the norm"*

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[47] UK Research and Innovation Corporate Plan 2020-21 (2020) https://www.ukri.org/wp-content/uploads/2020/10/UKRI-091020-CorporatePlan2020-21.pdf [*Accessed April 2021*]; UK Research and Innovation Delivery Plan (2019) https://www.ukri.org/wp-content/uploads/2020/09/UKRI-250920-DeliveryPlan2019.pdf [*Accessed April 2021*]

[48] NERC Delivery Plan (2019) https://www.ukri.org/wp-content/uploads/2020/09/NERC-250920-DeliveryPlan2019.pdf [*Accessed April 2021*]

[49] https://www.ukri.org/our-work/supporting-healthy-research-and-innovation-culture/equality-diversity-and-inclusion/edi-overview/ [*Accessed June 2021*]

Develop the data ecosystem with clear compliance with FAIR principles, with the required meta data and machine-readability to enable to start the adoption of machine learning/artificial intelligence (AI). **Encourage continued interaction between observational and modelling marine researchers.** **Develop ocean digital twins.**	Exploring the role of innovation, collaboration and participation in shaping cultural experiences	
Maintain a dialogue over the next five years between scientists and technology developers regarding the platform and sensor requirements needed for the effective delivery of key science goals.	Openness and transparency Forging connections to build confidence in the digital economy	Digital environment *“Exploit environmental data as a testbed for machine learning and analytics”*
Invest in discipline-specific requirements across the marine sciences.	Supporting a diverse research ecosystem	Pushing the frontiers of understanding *“Maintain and enhance UK’s position at the leading edge of science”*
Work with industry and other private sector partners to take advantage of technology already under development and open up new opportunities. **Work with other scientific organisations within and around the UK, including devolved governments, to ensure integration of approaches and efficiency in the journey towards a Net Zero future.**	Connecting communities to policy makers Incentivising new collaborations to tackle societal issues Encouraging private investment, and supporting private and public sector collaboration	Productive environment Environmental solutions Healthy environment Resilient environment Pushing the frontiers of understanding *“Fund institutions and institutional partnerships that draw together existing*

		capabilities and regional strengths, building new interdisciplinary capability" *"Support research that delivers and the systems and solutions that reduce consumption and inefficiency, maximise the productivity of the land and oceans while promoting biodiversity and minimising degradation"*
Improve efficiency of ships over the next decade, for when ship-based activities are required.	Funding to build high-quality capability Long-term investment plans for sustainable infrastructure Access to unique National and International facilities	Environmental solutions Pushing the frontiers of understanding *"Invest in research and innovation that uses cutting-edge technology to advance environmental outcomes"*
Develop a flexible hybrid system of "autonomy where possible" coupled with the continued operation of crewed research vessels over the next two decades, which can be made more efficient through improved co-ordination and data flow, would allow the UK to maintain their position as a world-leader in sea-going science and technology whilst also meeting Net Zero targets. **Adopt new approaches flexibly and in parallel with rigorous ground-truthing, calibration and quality control in order to improve trust of the emerging technology in the community over the next two decades.**	Sustainability and the environment Long-term investment plans for sustainable infrastructure Access to unique National and International facilities	Environmental solutions Pushing the frontiers of understanding *"Employ the wide range of sensor technologies now available to connect to and visualise the local and national environment, enabling real-time decision-making and the deriving of new insights across disciplines"*

Appendix 6: Stakeholder engagement report for WP1

Date	Contact(s)	Organisation(s)	Description
25/09/2020			Uni. Bristol news release, also posted on Twitter http://www.bristol.ac.uk/cabot/news/2020/marine-science-net-zero.html
04/12/2020		British Antarctic Survey	Promotional talk
11/11/2020		Scottish Association for Marine Science	Presentation
14/12/2020		NOC Association	Workshop 1 promoted via NOCA mailing list
14/12/2020		Challenger Society	Workshop 1 promoted through Challenger Society network
15/12/2020	Roslyn Gardener	PML	Email response to query from recipient of NOC Association communication
20/01/2021		NOC	Posted survey in NOC All Staff collaboration channel
19/01/2021		Workshop 1 Registered Participants	Email with joining details including link to survey
19/01/2021		WP1 EOIs	Email with link to survey
19/01/2021			Posted article with survey link on website
25/01/2021	Innovation Centre Members		WP1 survey posted in Innovation Centre monthly newsletter
22/01/2021		@NOCNews followers	WP1 survey shared on NOC Twitter
22/01/2021			WP1 videos posted on NZOC website
09/02/2021	Sarah Reed	SAMS	Focus group for WP1
15/02/2021	Barbara Berx	Marine Science Scotland	Focus group for WP1
17/02/2021	James Fishwick	PML	Focus group for WP1
30/03/2021	Mike Meredith, Alessandro Tagliabue	IPCC SROCC	Focus group for WP1
30/03/2021	Ros Coggan	UK IODP	Focus group for WP1
30/03/2021	Veerle Huvenne	NOC	Focus group for WP1
05/07/2021	Katy Hill	NOC	Focus group for WP1

Appendix 7: Glossary of terms

ADCP	Acoustic Doppler Current Profiler
ADF	Autonomous Deployment Form
AI	Artificial Intelligence
ALR	Autosub Long Range
AMOC	Atlantic Meridional Overturning Circulation
AMT	Atlantic Meridional Transect
ARCGOOS	Arctic GOOS
AS	Autosub
AUV	Autonomous Underwater Vehicle
BAS	British Antarctic Survey
BGC	Biogeochemical
BODC	British Oceanographic Data Centre
CARE	Collective benefit-Authority to control-Responsibility-Ethics
CCRA	Climate Change Risk Assessment
CFC	Chlorofluorocarbon
COVID	COVID-19 disease caused by the SARS-CoV-2 virus
CPRG	Cruise Program Review Group
CTD	Conductivity, temperature, depth
CV	Curriculum Vitae
DIC	Dissolved Inorganic Carbon
DNA	Deoxyribonucleic Acid
DOC	Dissolved Organic Carbon
DOOS	Deep Ocean Observing System
ECR	Early Career Researcher
ED(&)I	Equality/Equity, Diversity (and) Inclusivity
EM	Electromagnetic
EMB	European Marine Board
EOV	Essential Ocean Variable
EPSRC	Engineering and Physical Sciences Research Council
ERC	European Research Council
ESRC	Economics and Social Research Council
EU	European Union
FAIR	Findable-Accessible-Interoperable-Reusable
FOO	Framework for Ocean Observing
GHG	Greenhouse Gases
GO-SHIP	The Global Ocean Ship-Based Hydrographic Investigations Program
GOA-ON	Global Ocean Acidification Observing Network
GOOS	Global Ocean Observing System
GOSSIP	General Ocean Survey and Sampling Iterative Protocol
GPS	Global Positioning System
HE	Higher Education
HEI	Higher Education Institute
HMI	Human-Machine Interface
HPLC	High Performance Liquid Chromatography
IASC	International Arctic Science Committee
ICY-LAB	Isotope Cycling in the Labrador Sea

IODP	International Ocean Discovery Program
IPCC	Intergovernmental Panel on Climate Change
ISIS	Remotely Operated Vehicle *Isis*
JCOMMOPS	Joint Observing Program Support Centre
JCR	Royal Research Ship *James Clark Ross*
LADCP	Lowered Acoustic Doppler Current Profiler
LEO	Low Earth Orbit
MASTS	Marine Alliance for Science and Technology for Scotland
MCA	Marine and Coastguard Agency
MCCIP	Marine Climate Change Impacts Partnership
MINERVA	Maritime Industries Environmental Risk and Vulnerability Assessment
MOD	Ministry of Defence
MRC	Medical Research Council
MSCC	Marine Science Co-ordination Committee
MSS	Marine Scotland Science
NAP	National Adaptation Plans
NERC	Natural Environment Research Council
NEXUSS	Next Generation Unmanned Systems Science
NMEP	National Marine Equipment Pool
NMF	National Marine Facilities
NOAA	National Oceanic and Atmospheric Administration (US)
NOC	National Oceanography Centre
NZOC	Net Zero Oceanographic Capability
OBS	Ocean Bottom Seismometer
OSNAP	Overturning in the Subpolar North Atlantic Program
PAM	Passive Acoustic Monitoring
PAP	Porcupine Abyssal Plain (project)
PES	Parametric Echo Sounding
PI	Principal Investigator
PIC	Particulate Inorganic Carbon
PML	Plymouth Marine Laboratories
POC	Particulate Organic Carbon
POGO	Partnership for Observation of the Global Ocean
PSO	Principal Science Officer
PSS	Practical Salinity Scale
QA	Quality assurance
QC	Quality control
RAPID	Rapid Climate Change
RD&I	Research Development and Innovation
ROV	Remotely Operated Vehicle
RRS	Royal Research Ship
RV	Research Vessel
SAMBA	South Atlantic MOC Basin-wide Array
SAMS	Scottish Association for Marine Science
SAON	Sustaining Arctic Observing Network
SAP	Stand Alone Pump
SBP	Sub-bottom Profiler
SCOR	Scientific Committee on Oceanic Research
SDG	Sustainable Development Goals
SME	Ship-time & Marine Equipment
SOCCOM	Southern Ocean Carbon and Climate Observations and Modeling project

SOOS	Southern Ocean Observing System
SQEP	Suitably Qualified and Experienced Person
SROCC	Special Report on the Ocean and Crysophere in a Changing Climate
SWOT	Surface Water and Ocean Topography
TAlk	Total alkalinity
TPOS	Tropical Pacific Observing System
UKRI	UK Research and Innovation
UN	United Nations
USBL	Ultrashort Baseline
VOS	Voluntary Observation Ships
WOCE	World Ocean Circulation Experiment
WP1	Work Package One
XBT	Expendable bathythemograph

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