UK SUSTAINED SCIENTIFIC OBSERVATION PRIORITIES (SSOOP)

A CONSULTATION COORDINATED BY THE NATIONAL OCEANOGRAPHY CENTRE ON BEHALF OF THE NATURAL ENVIRONMENT RESEARCH COUNCIL

CONTENTS

ACRONYMS

ACOPS
Advisory Committee on the Protection of the Sea

AFBI-NI
Agri-Food and Biosciences Institute Northern Ireland

AMT
Atlantic Meridional Transect

AMOC
Atlantic Meridional Overturning Circulation

BAS
British Antarctic Survey

BGS
British Geological Survey

BTO
British Trust for Ornithology

CCO
Channel Coastal Observatory

Cefas
Centre for Environment Fisheries & Aquaculture Science

CPR
Continuous Plankton Recorder Survey

DAERA-NI
Dept Agriculture, Environment and Rural Affairs, Northern Ireland

DfT
Department for Transport

DOENI (now DAERA-NI)
Department of Environment Northern Ireland

EA
Environment Agency

EEZ
Economical Exclusion Zone

EOV
Essential Ocean Variable

EMB
European Marine Board

HS
Historic Scotland

IOZ
Institute of Zoology

JNCC
Joint Nature Conservancy Committee

GLOSS
Global Sea Level Observing System

GOOS
Global Ocean Observing Strategy

MBA
Marine Biological Association of the UK

MCA
Maritime & Coastguard Agency

MCS-UK
Marine Conservation Society UK

MFA
Marine and Fisheries Agency

MPA
Marine Protected Areas Survey

MSS
Marine Scotland Science

NE
Natural England

NERC
Natural Environment Research Council

NOC
National Oceanography Centre

NRW
Natural Resources Wales

PAP
Porcupine Abyssal Plain

PML
Plymouth Marine Laboratory

SAMS
Scottish Association for Marine Science

SEPA
Scottish Environment Protection Agency

SMRU
Sea Mammal Research Unit

SNH
Scottish Natural Heritage

SOOC
Ships of Opportunity

UKHO
UK Hydrographic Office

UKRI
UK Research & Innovation

WCO
Western Channel Observatory

WWT
Wildfowl and Wetlands Trust

FOREWARD

Following a request from UKRI-Natural Environment Research Council (UKRI-NERC), the National Oceanography Centre (NOC) initiated an open consultation, capturing views from across the marine science community, to prioritise the sustained ocean observations that are most important to the UK and the international effort.

After gathering the evidence, the NOC convened a workshop of experts to discuss the responses and identify the priorities. This report covers two aspects of sustained ocean observations: (a) the general drivers, frameworks and international and national context and (b) the considerations of research funders who support a high proportion of the ocean observing systems. It is hoped this report will help inform dialogue and enhance a mutual understanding of the perspectives, both of those who make and use observations and those who fund them.

ACKNOWLEDGEMENTS

I would like to thank UKRI-NERC for their on-going support to UK marine science, the contributors to the online survey and the NOCA June 2022 workshop. Special thanks to the membership of the Panel - Professor Sheila Heymans (Executive Director, European Marine Board, Chair), Dr Bee Berx (Marine Scotland Science), Dr Ken Johnson (Monterey Bay Aquarium Research Institute), Professor Alberto Naveira-Garabato (University of Southampton), Professor Carol Robinson (University of East Anglia), Professor Martin Visbeck (GEOMAR Helmholtz-Centre for Ocean Research Kiel), Professor Anya Waite (Ocean Frontier Institute, Halifax, Canada) and Dr Richard Wood (The Met Office) - for their thorough review of the results and to Professor Angela Hatton (National Oceanography Centre).

In writing this report, I would like to thank Dr Cristian Florindo-Lopez for preparing the data and Professor Penny Holliday, Dr Ben Moat, Dr Matthew Palmer, Simon Beasley and Alan Evans and for their contributions of text, figures and diagrams.

Final thanks to Project Manager, Dr Kristian Thaller and to Cait Allen, David Boot, Ian Folger, Jackie Pearson and Stacey Greenwood for their support.

Professor Ed Hill CBE
Chief Executive
National Oceanography Centre

Cover: Cleaning an Ocean Data Acquisition Systems (ODAS) buoy on board the RRS James Cook in the Porcupine Abyssal Plain.
Jackie Pearson, NOC

EXECUTIVE SUMMARY

1. Ocean observations benefit research, weather forecasting, resource and environmental management and human health. In this report, eleven UKRI-NERC funded, mostly open ocean, sustained in situ observation systems, including two within the UK EEZ, have been reviewed.

2. For scientific purposes, sustained duration observations are needed when processes have one or more of the following characteristics: (a) large space-time scales of change and variability, (b) are intermittent, needing long, continuous data series to detect events (c) a large noise/variability to signal ratio needing extended duration measurements to detect signals. Provision of data for assimilation into operational forecast models and digital twins may also need continuous ocean measurements sustained over long durations.

3. Priorities in the Global Ocean Observing System (GOOS) 2030 Strategy are to (a) expand spatial and temporal coverage of in situ ocean observations, (b) expand coverage of Essential Ocean Variables (EOV), (c) increase the number of ocean observations that are supported by sustained funding. Only ~ 30% of *in situ* ocean observations have sustained funding, against the 72% of atmospheric observations which are supported by core institutional funding (Buch *et al.* 2019).

4. Although the consultation recommends that all these observing systems are of value and should be continued, if possible, there are nuances which are explored.

5. The following observations are priority: Atlantic Meridional Overturning Circulation, Global Sea Level Observing System, ARGO, GO-SHIP, the Continuous Plankton Recorder and the Ellett Array. Three never appeared in the bottom: AMOC, ARGO and GO-SHIP. The Ship of Opportunity Ocean Surface Carbon Programme has effectively ceased. Surface carbon measurements need to be increased and measurements moved to autonomous surface platforms. Some observations provide core measurements of EOV and are a platform for a wider range of projects. These are beneficial but distinct from the function of sustaining core EOVs. The question of scale of some observations was raised, with some appearing to entail intensive activity, which implied relatively high costs (e.g., PAP, WCO). It was queried whether some could be better scaled, in terms of sampling frequency or range of variables observed, especially if funding is constrained. Some observing systems e.g. AMOC and Ellett Array had previously been scaled back. The panel felt the relative costs should be considered in relation to benefits.

6. Opportunities for technology innovation and greater use of autonomous platforms are considered. Nevertheless, there are challenges in maintaining data quality for long-unattended ocean sensors on such platforms, let alone more complex biogeochemical and biological ocean variables. Consequently, parallel running with established high accuracy methods where absolute calibration is possible (e.g., ship-based data like GO-SHIP) is emphasised. A priority area for innovation is to measure ocean surface carbon variables accurately using un-crewed surface vehicles.

PART 1: THE OCEAN

1. The ocean covers 70% of the Earth's surface and comprises 97% by volume of its biosphere. Its ecosystem services sustain life and wellbeing, including regulating the climate and recycling half the oxygen through marine plankton. Over 1 billion people depend on the ocean for their main source of protein. Today, however, the ocean is subject to the cumulative impact of multiple pressures from human activities, climate change, pollution, over exploitation and habitat destruction which threaten the very ecosystems we rely on, to underpin 80% of the direct economic value created from the ocean.

2. The ocean is an environmental, economic, geopolitical, security, technological and scientific frontier where systematic data and information gathering is essential to inform decision making and policy actions.

3. Managed sustainably, the ocean may offer solutions to the greatest challenges of our age. Marine-based solutions, including renewable energy, sustainable food, restoration of natural carbon sinks, could fill up to 20% of the gap between today's CO_2 emissions and those needed meet the Paris target of limiting global warming to 1.5°C (Hoegh-Guldberg, *et al.* 2019). The ocean economy is projected to grow from US$1.5 to 3.0Trillion from 2015 to 2030 (OECD, 2016). We need to better understand the risks posed by the ocean to humanity and humanity to the ocean.

4. Some 80% of direct economic benefits from the ocean are underpinned by healthy marine ecosystems which are under increasing threat due to the cumulative impacts of climate change, over-exploitation of resources, pollution and habitat degradation (Hoegh-Guldberg *et al.* 2015).

5. Scientific knowledge, understanding and timely information from the ocean, underpinned by reliable systematic data, is needed to:
   - protect and reverse decline in the health and productive capacity of threatened marine ecosystem services; (Hoegh-Guldberg *et al.* 2015);
   - investigate and make sense of the fundamental processes of change and variability that operate in the marine-earth system National Research Council (2011);
   - increase resilience of coastal populations to marine related hazards and accidents (UNISDR, 2015);
   - sustainably manage development of an equitable ocean economy (OECD, 2016a).

6. There are major gaps in even basic knowledge about the ocean which, for most of the 20th century, was grossly under-sampled in space and time (unlike the atmosphere which has been relatively well observed to support weather forecasting and the terrestrial system which is much more visible and accessible to investigation).

7. The ocean is a challenging environment to measure and satellites, whilst providing extensive global and regional coverage, mostly see only thin surface skin. Building the sub-surface ocean sensing network 'Internet of Things' (IoT) is crucial, despite the challenges to underwater data communications, instrument resilience, corrosion and sub-sea pressures. However, great progress has been made in technological innovation in the first two decades of the 21st century.

DRIVERS FOR SYSTEMATIC SUSTAINED OCEAN OBSERVATIONS

8. Human society is confronted by what is increasingly recognised as two interlinked environmental crises – climate change and biodiversity loss - which require concerted, coordinated global actions and solutions informed by science.

9. These issues and solutions are interlinked. e.g., whilst climate change is one of the cumulative stressors on ecosystems risking biodiversity collapse, the protection, restoration and enhancement of ecosystems can help mitigate (e.g., restore natural carbon sinks) and support adaptation to climate change to which we are already committed (e.g., food security, coastal resilience).

10. Some statistics about the role of the ocean in earth system processes point to its importance and demonstrate why sustained ocean observations are crucial to the scientific and societal challenges relating to the ocean (Figure 1).

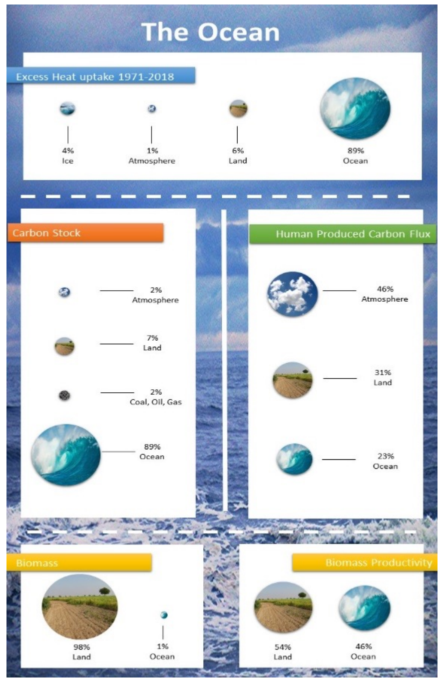


Figure 1: The role of the ocean in heat and carbon uptake.

11. The ocean takes up and redistributes about 90% of excess global warming heat (52% in the upper 700m the rest deeper) and its modes of couple ocean-atmosphere variability directly impact seasonal weather and climate experienced on land. Warming ocean waters and melting ice sheets are causing global sea level rise, one of the clearest and most directly impactful consequences of global heating.

12. The ocean provides the largest mobile above ground carbon stock on earth (90%), holding 50 times more carbon than the atmosphere and it takes up about a quarter of anthropogenic CO_2, some of which is then sequestered in the deep ocean for centuries to millennia Carbon gets into the deep sea by dissolving in surface waters and being subducted into deeper waters by the ocean's overturning circulation - mainly in the North Atlantic and Southern Oceans and by being taken up by growing marine plant plankton primary production in sunlit surface waters and by secondary biological production by zooplankton and high trophic levels which sinks into the deep sea and sea floor as these organisms die and excrete (biological carbon pump).

13. Ocean biomass is estimated to be about 80 times less than that on land but despite its tiny comparative size the rate of production of new biomass is about the same as that of all land biomass (Figure 1). Ocean food-webs (where only about 1billion tonnes plant biomass sustains about 5 billion tonnes of animal biomass) are inverted compared to the land where about 450 billion tonnes of plant biomass support about 20 billion tonnes of animal biomass. This means that the small ocean biomass is 'running hot' as it turns over at very fast and sustains a large biodiversity. The underlying reason for this difference is that, unlike on land, there is separation in depth between where availably light for photosynthesis is (surface ocean) and where the main reservoirs of nitrogen and phosphorous nutrients are (deep waters). Consequently, ocean productivity is strongly controlled by physical ocean processes and where energy is needed to enable deeper waters to be lifted into the surface layers (circulation, upwelling, mixing).

14. The fast-running ocean system (Figure 1) risks being unstable and is highly susceptible to change and variability in ocean physical and biogeochemical properties. Fossil fuel emissions targets are predicated on the tacit assumption the ocean will continue taking up and sequestering carbon at present rates, but this cannot be presumed. Indeed, important climate trends – warming surface waters (less dissolved CO_2); freshening subpolar waters (reduced subduction by the overturning circulation); more stratification (greater restriction on nutrient fertilisation of upper waters from below fuelling the biological carbon pump), point to slowing of ocean carbon uptake – not to mention biomass production impacts of ocean de-oxygenation, acidification, and poleward movement of warm water plankton species. There remains uncertainty in the stability of large-scale ocean carbon sinks and even the sign of those (sink versus source) over large areas.

15. Understanding, quantifying and gaining predictive capability about these impacts which operate at whole-basin and global scales needs systematic ocean data gathering over extended durations and demonstrates firmly why sustained, globally distributed ocean observations is so central a methodology for addressing the key scientific questions about

the rates (and even sign) and tipping points in this potentially highly unstable ocean system which data from past climates shows to be capable of rapid physical, biogeochemical and ecological state changes.

16. The large-scale changes which operate at global and basin scales over timescales of decades or more have local expressions which vary from region to region. Moreover, these climate drivers (at rates unprecedented in earth history) of biodiversity change are compounded – especially closer to the coast in the crowded, economically active waters of the ocean margins, continental shelves and coasts - by cumulative other human pressures (pollution, habitat degradation, and over exploitation of resources). These impacts are more specific and localised, driven by large-scale change and variability, local and regional variability (e.g., weather, river discharges, sedimentation) and more localised direct human impacts.

17. For these reasons, systematic global-scale observations are needed to understand the main drivers of change (heat and carbon uptake and storage) and their effects on physical and biogeochemical consequences (sea level rise, de-oxygenation, acidification). Regional-scale observations are important to track resultant ecological impact which may be compounded by natural and human forcing. Global scale biodiversity loss may result.

SCOPE OF OBSERVATIONS CONSIDERED

18. Different types of observations are made for different motivations (e.g., the range of UK marine measurements are listed in Appendix 2 and represented in Figure 2.) Only a sub-set of these fall within the scope of this report which aims to assist UKRI-NERC prioritise its investments in sustained ocean observations, primarily motivated by generating new knowledge and understanding of the ocean-earth system and with beneficial wider impacts of that knowledge.

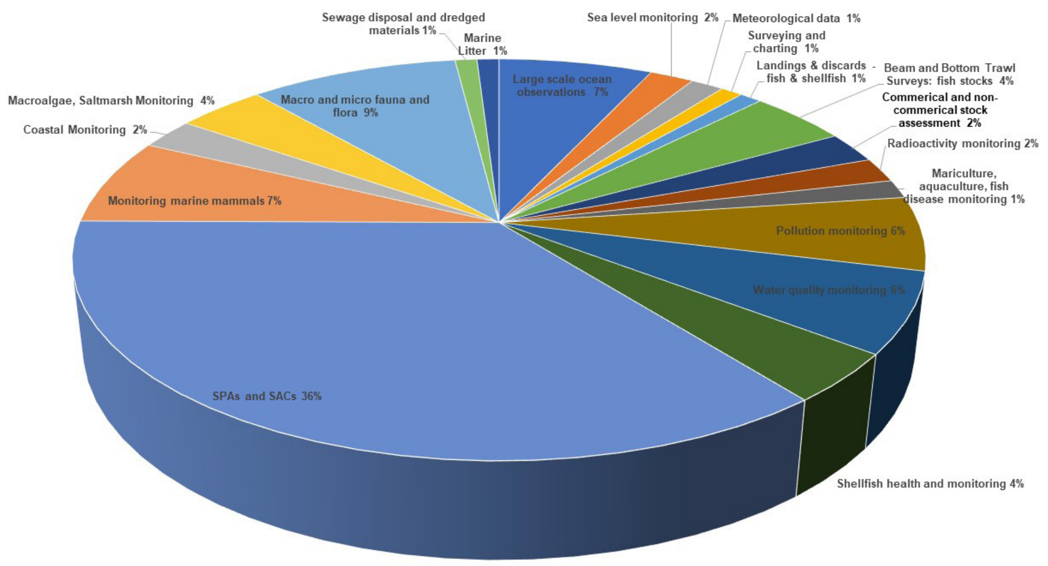


Figure 2: UK Marine and Ocean Observing Programmes shown by percentage.

The large-scale ocean observations (7%) include *UKRI-NERC funded sustained observations: Ellett Line, the Atlantic Meridional Overturning Circulation, the Atlantic Meridional Transect, the Argo, Ship of Opportunity and Go-Ship Programmes, the Western Channel Observatory, the Global Sea Level Observing System and the Porcupine Abyssal Plain. The macro and micro fauna and flora (9%) monitoring programmes include UKRI-NERC funded sustained observations: Continuous Plankton Recorder Survey and the Marine Protected Areas.*

Delivery organisations, agencies, companies: *Advisory Committee on the Protection of the Sea, Agri-Food and Biosciences Institute, British Antarctic Survey, British Geological Society, British Antarctic Survey, British Trust for Ornithology, Centre for Environment, Fisheries and Aquaculture Science, Coastal Channel Observatory, Department of Environment (Northern Ireland), Department of Agriculture, Environment and Rural Affairs, Environment Agency, Food and Environment Research Agency, Institute of Zoology, Isle of Man Marine Water Monitoring Programme, Joint Nature Conservation Committee, Marine Biological Association, Marine Conservation Society, Marine Fish Recording Scheme, Marine Scotland Science, Met Office, Napier University, National Oceanography Centre, Natural Resources Wales, Natural England, Newcastle University, Plymouth Marine Laboratory, Scottish Association for Marine Science, Scottish Environment Protection Agency, Scottish National Heritage, Sea Mammal Research Unit, Sea Watch Foundation, Shell PLC,Tritonia Scientific, University College Cork, University of Edinburgh, University of Southampton, Wildfowl and Wetlands Trust.*

19. The subset of observations in scope (Figure 3) are:

- systematic and sustained – not ad hoc or one-off measurement campaigns;
- where advancement of knowledge is the primary motivation – not primarily for monitoring the outcome of and compliance with a specific marine management policy;
- For public benefit – data available in a timely way and openly accessible;
- Earth-based - in situ (in water) or remotely sense from shore, but not satellite based;
- where UKRI-NERC funds the observations in whole or in part and specifically from its marine science (rather than earth or polar science) budget lines.

20. Observations considered span from coast to deep ocean; those reviewed are in the Atlantic Ocean and Atlantic sector of the Southern Ocean (the main basin-scale area of UK activity concerning sustained ocean observation contributions to global networks).

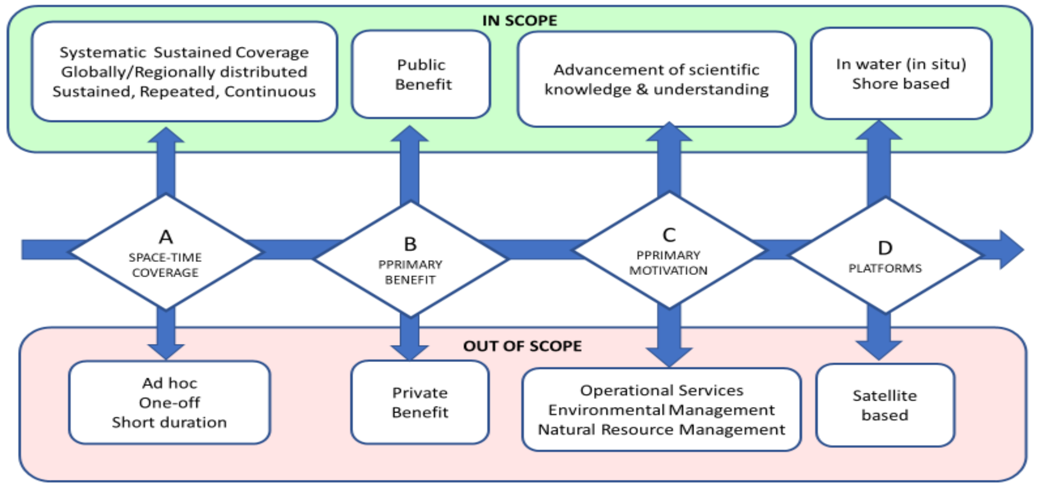


Figure 3: The subset of observations in scope

DEFINITIONS

21. The following relate to the filters applied in Figure 3 and provide clarity in discriminating between the wide range of ocean observations that take place.

PUBLIC BENEFIT

22. Public benefit activities are distinct from those providing private benefit unless that private benefit is incidental to the primary public benefit purpose.

23. Advancement of scientific knowledge and understanding is recognised as public benefit, as are other activities supported and enabled by information from ocean observations, e.g., environmental protection and public safety.

24. A useful test as to whether an observational activity is supporting public benefit, rather than narrower, private benefits, is whether the data generated are openly accessible and available. If not, the likelihood is that a private, or possibly national security, benefit is being served.

25. Some private sector data are not openly accessible because of, for example, commercial value/sensitivity, however,

private sector contributions to ocean observations can lead to public benefit in the following instances:

- development and manufacture of commercially available ocean sensors and platforms;
- provision of commercial platforms, such as ships of opportunity, from which observations are made;
- release of commercially obtained data in real-time delayed mode for synthesis into global and regional data sets;
- emerging 'data as a service' commercial business models for making observations for public agencies;
- creation of added value, commercially available information products from openly accessible public good data.

SCIENTIFIC MOTIVATION FOR OCEAN OBSERVATIONS

26. This report reviews some of the motivations for undertaking systematic sustained ocean observations, to provide context for focus on those where the primary motivation is Research and Development (R&D), for the advancement of scientific knowledge and understanding.

27. Confusion about the purpose of observations can lead to lack of clarity about responsibility for funding. The Frascati definition of R&D states that research and experimental development (R&D) comprises creative and systematic work undertaken in order to increase the stock of knowledge – including knowledge of humankind, culture and society – and to devise new applications of available knowledge. The term R&D covers basic, applied research and experimental development (OECD, 2015).

    - **Basic research** is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundation of phenomena and observable facts, without any particular application or use in view.
    - **Applied research** is also original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific practical aim or objective.
    - **Experimental development** is systematic work, drawing on existing knowledge gained from research and/or practical experience, which is directed to producing new materials, products or devices, to installing new processes, systems and services, or to improving substantially those already produced or installed. R&D covers both formal R&D in R&D units and informal or occasional R&D in other units.

28. Whilst scientific research may be the primary motivation for undertaking observations, there is often an expectation for societal benefit. The UK's Research Excellence Framework (REF) defines 'impact' as "an effect on, change or benefit to the economy, society, culture, public policy or services, health, the environment or quality of life, beyond academia." (UKRI 2022).

29. Delivering 'impact' from 'R&D' (as both are defined) should be distinguished from undertaking observations for motivations that are not R&D. (e.g., routine environmental management monitoring or weather forecasting). In some cases, developing new methods or trialling or demonstrating monitoring or forecast observational approaches may constitute 'experimental development ('D' in 'R&D').

30. In a multi-stakeholder environment for ocean observing, it is important to be clear about expectations. Even where ocean observations are not primarily motivated by scientific aims, there is considerable technical skill and scientific expertise needed to make and interpret them. Involvement of scientists in ocean observations can lead to confusion as to whether observations are scientifically motivated or not. For these reasons, it is useful to refer the Frascati definition. Moreover, sustained observations not primarily made for scientific purposes (e.g. weather forecasting, pollution monitoring) can, especially when integrated with other data, have scientific research value. Hence, there are likely to be multiple beneficiaries of sustained observations regardless of the primary motivation for making them.

SYSTEMATIC, SUSTAINED OBSERVATIONS

31. Whilst 'one-off', time-limited, ad hoc ocean observations are beneficial, they are insufficient to track and understand the scale of changes described or provide the systematic evidence base needed to inform international ocean actions at scale, around which consensus can be built.

32. Consequently, action-orientated ocean science increasingly needs observations that are:

    - **Systematic** – to cover the space-scales needed with international cooperation to achieve this, with consistent sampling methodologies to enable global- and regional-scale data syntheses.
    - **Sustained** – to cover the timescales (multi-decadal) involved commensurate with the space scales entailed and to detect and attribute signals of change from natural variability and other causes of change. Some observations are made continuously on an indefinite basis and are sustained by definition. A minimal definition of 'sustained' was used by the European Global Ocean Observing System (EuroGOOS) as of seven years duration or longer.

THE SCIENCE AGENDA - DECADE OF OCEAN SCIENCE

33. The scale of challenges facing the Planet is why scientists, from all over the world, have come together to declare 2021 to 2030 as the UN Decade of Ocean Science for Sustainable Development 2021- 2030 (the Ocean Decade).

34. The vision of the Ocean Decade, 'the science we need for the ocean we want' will use transformative science solutions to achieve the following seven 'Decade' outcomes:

    - A **clean ocean** - sources of pollution are identified and reduced or removed.
    - A **healthy and resilient ocean** - ecosystems are understood, protected, restored and managed.
    - A **productive ocean** - supporting sustainable food supply and a sustainable ocean economy.
    - A **predicted ocean** - society understands and can respond to changing ocean conditions.
    - A **safe ocean** - life and livelihoods are protected from ocean-related hazards.
    - An **accessible ocean** - open, equitable access to data, information, technology and innovation.
    - An **inspiring and engaging ocean** - society understands and values the ocean in relation to human well-being and sustainable development.

35. Ten challenges have been identified to achieve the seven 'Decade' outcomes. They are underpinned by three interrelated, infrastructure challenges including Challenge Seven: '*ensuring the sustained ocean observing system*'. This entails moving beyond short-term, periodic measurements to global ocean sensing and the digital data infrastructures needed to tackle the biggest science questions about basin-global decadal scale change and variability, and to translate to effective science-based ocean assessments, actions and solutions ('*cannot manage what you cannot measure*').

THE TEN OCEAN DECADE CHALLENGES

SCIENTIFIC KNOWLEDGE AND SOLUTIONS

- **One** - Understand and map land and sea-based sources of pollutants and contaminants and their potential impacts on human health and ocean ecosystems and develop solutions to mitigate.

- **Two** - Understand the effects of multiple stressors on ocean ecosystems, and develop solutions to monitor, protect, manage and restore ecosystems and their biodiversity under changing environmental, social and climate conditions.
- **Three** - Generate knowledge, support innovation and develop solutions to optimise the role of the ocean in sustainably feeding the world's population under changing conditions.
- **Four** - Generate knowledge, support innovation, and develop solutions for sustainable development of the ocean economy under changing conditions.
- **Five** - Enhance understanding of the ocean-climate nexus and generate knowledge and solutions to mitigate, adapt and build resilience to the effects of climate change across all geographies and at all scales, and to improve services including predictions for the ocean, climate and weather.

ESSENTIAL INFRASTRUCTURE

- **Six** - Enhance multi-hazard early warning services for all geophysical, ecological, biological, weather, climate and anthropogenic related ocean and coastal hazards, and mainstream community preparedness and resilience.
- **Seven** - Ensure a sustainable ocean observing system across all ocean basins that delivers accessible, timely and actionable data and information for all. Challenge seven seeks to expand the Global Ocean Observing System (GOOS) which provides information on physical, chemical, and biological variables, aimed at delivery for climate, operational services, and ocean health.
- **Eight** - Through collaboration, develop a digital representation of the ocean, including a dynamic ocean map, which provides free and open access for exploring, discovering, and visualizing past, current, and future ocean conditions in a manner relevant to diverse stakeholders.

FOUNDATIONAL

- **Nine** - Ensure comprehensive capacity development and equitable access to data, information, knowledge and technology across all aspects of ocean science and for all stakeholders.
- **Ten** - Ensure that the multiple values and services of the ocean for human wellbeing, culture, and sustainable development are widely understood, and identify and overcome barriers to behaviour change required for a step change in humanity's relationship with the ocean.

36. Ocean Decade 'essential infrastructural challenges' aim to provide systematic, timely and accessible data. Challenge Seven concerns completing progress to a global ocean observing system and expanding its spatial and parameter coverage. Observing on its own is insufficient because the product of observations is the generation of a value chain of data and information for science and for action. Science and observations are integral to informing and evaluating action. Information based on systematic, sustained ocean observations is essential for:
    - understanding how fundamental processes work in ocean change and variability including rapid, non-linear tipping points in ocean-state and ecological-regimes;
    - providing the basis for predictive capability e.g., ocean models and digital ocean twins;
    - providing scientific basis for action by governments, intergovernmental processes and policy makers and others in ocean affairs;
    - providing the baseline and tracking effectiveness of management and policy decisions.

THE OCEAN INFORMATION VALUE CHAIN

37. Ocean observations are at the base of a data and information value chain (Figure 4), the pinnacle of which is 'public benefits' which may include advancement of scientific knowledge, informed public policy interventions, and timely hazard warnings. (The technical parts of the information value chain from observations to digital representation and interpretation tools is detailed in the Decade's infrastructural challenges.)

38. Parts of the value chain interact and all would benefit from being strengthened. However, in water observations are foundational to full four-dimensional space-time characterisation of ocean change and variability and are costly and difficult to sustain. There would be no value chain or data innovations without them (e.g., like an Ocean Internet-of-Things or Digital Twins of the Ocean). This is recognised at the highest political levels (e.g., G7 Charlevoix Blueprint, 2018) which require in water ocean observations to be more sustainable.

39. Consequently, the observations part of the value chain is the focus of this report, and their prioritisation requires assessment of their added value benefit.

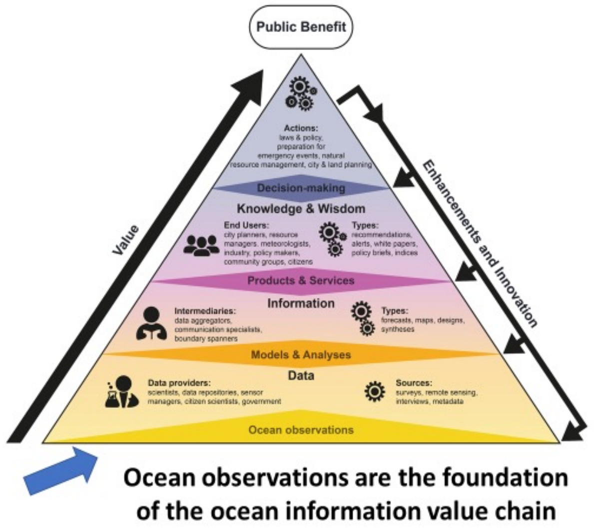


Figure 4: The ocean observation value chain. Adapted from Virapongse, et al. (2020). Ten Rules to Increase the Societal Value of Earth Observations. Earth Science Informatics 13(2): 233-47. CC-BY 4.0 taken from European Marine Board Policy Brief (June 2021).

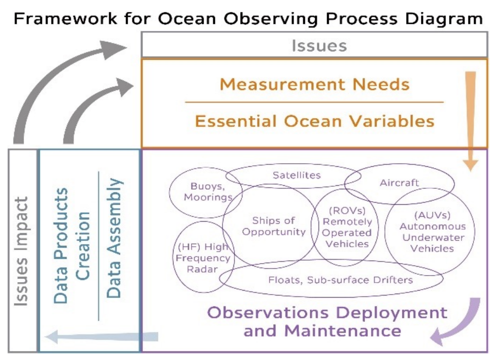


Figure 5: Framework for Ocean Observing (Tanhua T, *et al.* 2019)

40. The Framework for Ocean Observing (2012) (Figure 5) shows that the observation system is driven by the need for data and information.

OCEAN VARIABILITY

41. Systematic, sustained ocean observations are challenging because the ocean is variable across a vast range of space-time-depth scales (Figure 6. The big scientific questions involve identifying and attributing human-induced change from natural variability, e.g., how might these changes interact producing 'cascades of change', including those resulting in fundamental and rapid shifts in state of physical, biogeochemical and ecosystems.

42. The space-time scale of variability has implications for how processes are investigated. e.g.
    - long time-scale processes (millennia to millions of years) can be investigated using the Earth's natural records (e.g., tree-rings) for which sampling is the core methodology;
    - short time-scale processes (e.g., turbulence) and rate quantification (e.g., plankton photosynthesis) can often be investigated through specific 'one-off sets' of observations in specific locations or by laboratory experiments.

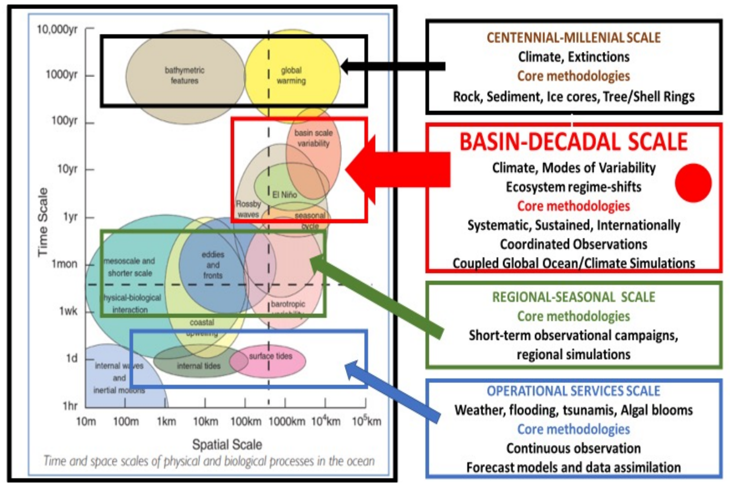


Figure 6: The ocean is variable at all scales. With different observational and sampling methodologies appropriate for each. (LHS image from Scanning the Horizon (2013) and annotation by Ed Hill, NOC).

WHEN SUSTAINED OCEAN OBSERVATIONS ARE THE METHODOLOGY OF CHOICE

43. Sustained ocean observations enable investigation of 1.) processes with large-scale, long-term phenomena; 2.) detection of signals and trends against backgrounds of low signal to noise ratio or where there is large background natural variability; 3.) intermittent phenomena or rapid system state-changes/regime- shifts/tipping-points where continuous observations are needed.

44. As it is not possible to replicate measurements, continuity of data is important. Replication may be achieved by using combining data with simulation models and digital twins which allow multi-model scenarios and parameterisation to explore uncertainty and variability. e.g., Coupled Model inter-comparison Project (CMIP) used in IPCC assessments. Consequently, a fourth motivation is re-initialising, constraining and assimilating into ocean simulation and other digital tools permitting scientific multi-ensemble scenario, hypothesis and predictive skill testing.

45. In other disciplines, problems with scale can be tackled without the need for sustained observation in particular locations. e.g., in astronomy, intermittent events like supernovae can be detected because there are billions of stars to be sampled. The fact that there is only one continually changing ocean (the 2023 ocean can never be revisited) makes sustained observation, as change unfolds, the core methodology, especially at the basin-decadal scale.

DIVERSITY OF OCEAN OBSERVING PLATFORMS

46. The range of space-time-depth scales has implications for the way ocean observations are made. Different sensor-carrying 'in water' platform types can meet different demands across the space-time-depth-parameter domain. No one platform type can cover meet all requirements or carry all the relevant sensors or sampling devices needed (Table 1). Thus, in water ocean observation systems are characterised by diversity, both in types of sensor and sensor-carrying platform, in contrast to space-borne measurements where diverse remote sensors are carried on essentially similar satellite platforms (either geo-stationary or polar-orbiting).

47. Satellite-based observations tend to measure only the thin surface skin of the ocean (although sometimes sub-surface properties can be inferred), however, subsurface, in-water (in situ) observations are essential for:

- measurement of the bulk of sub-surface properties not measurable by satellites;
- measurement of ocean properties for which no satellite-based sensors exist;
- ground-truthing satellite measurements.

Table 1: Ocean observations depend on a diverse range of platforms and sensors with no one platform type able to cover the space-time-depth-parameter space needed.

	Class of observing element (platform and sensors)	Nature of measurement	Areal coverage	Spatial resolution	Depth range	Sampling frequency	Number of variables measurable	Accuracy of sensors	Volume, bulk & energy demand of sampling
1	Research ships	Repeated hydrography, servicing of other platforms, biology, cores	Med	Med	High	Low	High	High	High
2	Voluntary observing ships	Surface weather, temp, salinity, carbon, plankton	Med	High	Low	High	Low	High	Med
3	Profiling floats	Temperature, salinity, some biogeochemical EOV	High	Low	Med	High	Low	Med	Low
4	Fixed buoys and other arrays	Subsurface physics, acoustics, biogeochemistry, biology	Low	Low	High	High	Med	High	Low
5	Drifting buoys	Surface properties, ice	Med	High	Low	High	Low	High	Low
6	Autonomous vehicles	Gliders, AUV, USV	Med	High	Med	Med	Med	Med	Low
7	Animal borne sensors	Location, temp, salinity, physiological variables	Med	High	Med	Med	Low	Med	Low
8	Seabed landers and cables	Seabed temp, seismicity, bottom pressure	Med	Med	High	High	Low	High	Med
9	Sea level gauges	Sea surface height relative to land	Med	Low	Low	High	Low	High	Low
10	Current/wave radars	Surface currents and waves	Med	High	Low	High	Low	High	Med
11	Low Earth orbit satellites	Sea level, temp, salinity, wind, roughness, ice, colour	High	High	Low	Med	Low	High	Low
12	Geo-stationary satellites	Sea surface temperature	High	Low	Low	High	Low	High	Low

- Surface and sub-surface 'in water'
- Seafloor based
- Coastal based
- Space based

THE GLOBAL OCEAN OBSERVING SYSTEM (GOOS)

48. The necessary coverage of ocean observations to address global- and basin-decadal time-scale questions can only be achieved through planned and coordinated international cooperation.

49. Since 1991 Global Ocean Observing System (GOOS) (Figure 7) has provided the framework through which most global-scale systematic, sustained observations are made. GOOS is a 'system of systems' comprising space-borne and in situ systems based on major sensor carrying platform types (e.g., drifting buoys, ship-based observations, profiling floats etc).

50. GOOS is sponsored at intergovernmental level. GOOS ocean observations constitute the Earth-based Ocean components of the Global Climate Observing System (GCOS) and the Global Earth Observing System of Systems (GEOSS).

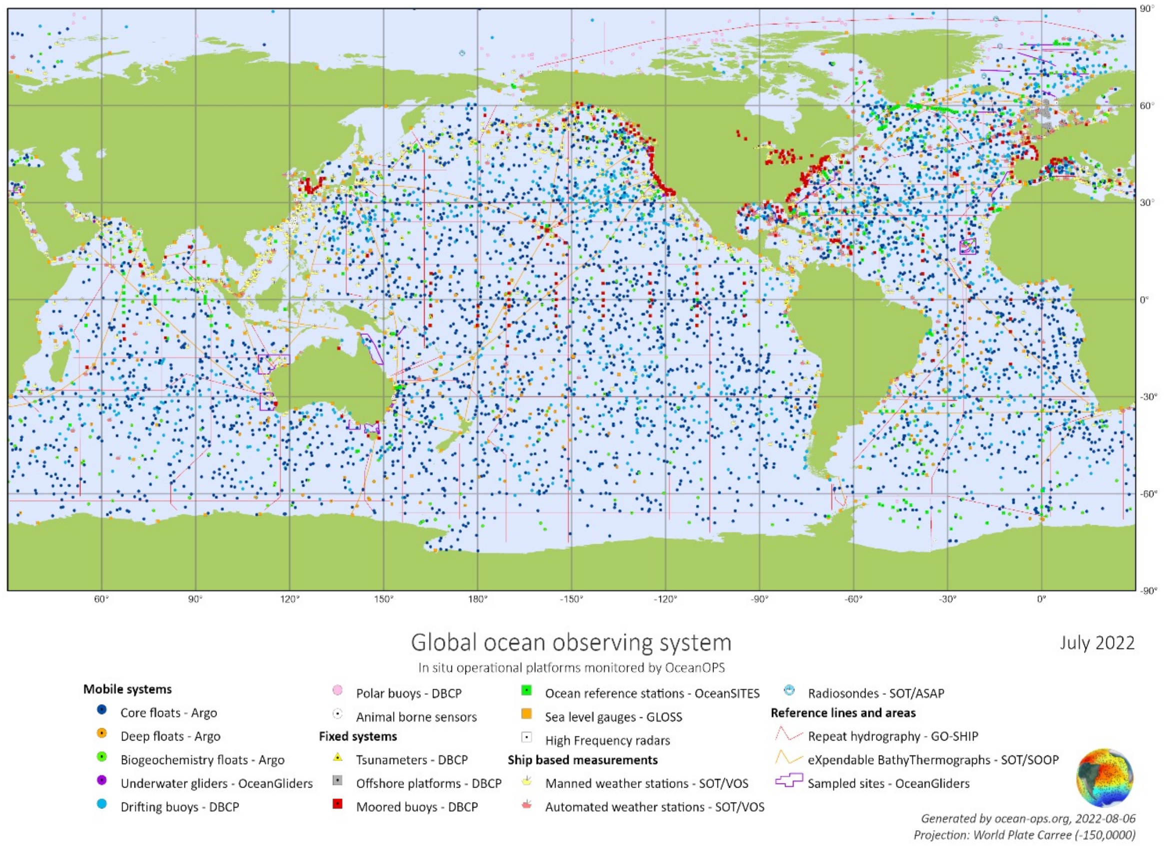


Figure 7: The Global Ocean Observing System is a 'system of systems' and its major component systems are shown. (Credit: ocean-ops.org 22-08-6)

51. The GOOS 2030 Strategy (IOC, 2019) sets out the drivers and benefits for sustained systematic ocean observations are in the fields of:

- climate
- ocean Health (Ecosystems, environment, living resources)
- operational Services (forecasts and warnings).

52. GOOS aims to serve multiple stakeholder interests, of which scientific research is one. The co-sponsorship of GOOS at international level reinforces multiple stakeholder interests in the 'value chain (Figure 3) and the international co-sponsor organisations of GOOS (the UK is a founding and active member of them all) are:

Non-governmental co-sponsors

- International Council for Science (ICS), comprising National Academies of Science and equivalents.

Inter-governmental (UN) co-sponsors

- the Intergovernmental Oceanographic Commission of United Nations Educational Scientific and Cultural Organisation (IOC-UNESCO).
- the United Nations World Meteorological Organisation (WMO).
- the United Nations Environment Programme (UNEP).

53. GOOS has not yet reached optimal levels of completion for its initial range of EOVs (see below), let alone develop the technologies needed to tackle all biogeochemical and ecological variables.

54. There is no international level funding for GOOS; almost all funding comes from national sources (and in some cases the European Union) aligned with the aims of GOOS or other national and international drivers for sustained observational data. The main source of funding for systems in areas beyond national jurisdiction (open ocean GOOS) come from Scientific Research funders and National Meteorological Services (but focus on upper ocean weather related variables).

55. There has been commentary (EMB, 2021) about the risk posed to GOOS resilience by dependence on R&D funding and on sustained, versus short term, funding that supports ocean observations, compared to meteorological observations. Currently, only ~ 30% of in situ ocean observations have sustained funding, against the 72% of atmospheric observations which are supported by core institutional funding (Buch et al. 2019). Completing a sustainable global ocean observing system is a transformative aim of the Ocean Decade.

56. The stability of GOOS depends on national funding so agencies like NERC-UKRI are important. National R&D funding agencies are encouraged to identify long-term funding lines that can support sustained ocean observing which focus on the large space-time scale science questions and development of science-informed solutions.

ESSENTIAL OCEAN VARIABLES AND MARINE INDICATORS

57. Building on the concept of Essential Climate Variables (ECV) defined by the Global Climate Observing System (GCOS), the Framework for Ocean Observing (UNESCO 2012) elaborated the concept of Essential Ocean Variables (EOV), which are those core parameters important to measure systematically, and to common standards, as far as possible, for subsequent data integration.

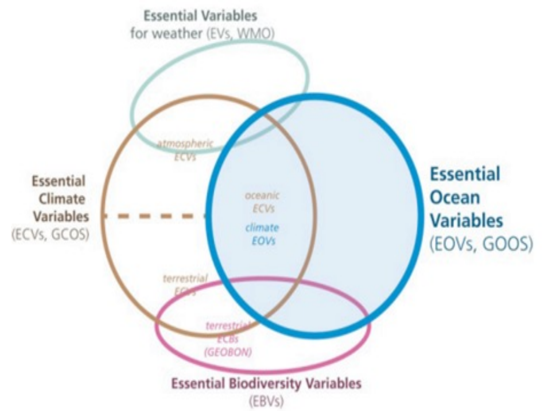


Figure 8: Essential Ocean Variables. Credit: A Framework for Ocean Observing. By the Task Team for an Integrated Framework for Sustained Ocean Observing, UNESCO 2012, IOC/INF-1284, doi: 10.5270/OceanObs09-FOO

58. EOVs are integral to the strategy for the GOOS (Figure 8 and Appendix 1). To date, the most mature EOVS are physical ocean climate-related variables, in terms of the readiness levels of the technologies to measure them in sustained ways, using sensors.

59. A priority for ocean observing is to expand the range of 'pilot' and 'mature' variables to biogeochemical and ecological parameters which will enable scientifically motivated ocean observations to make greater societal impact and support a bigger range of 'indicators' used for marine environmental monitoring.

60. Diversifying ocean sensing to more biogeochemical and ecological variables is the subject of considerable investment

in sensor technology development and innovation.

61. Care is needed because even straightforward physical parameters, which have been measured for decades (e.g., ocean salinity and oxygen), remain challenging to measure accurately and with stable calibration, when measured over long durations on unattended platforms, such as moored buoys and profiling floats. Accuracy is particularly important in the vast volume of the deep sea where spatial and temporal variability is lower than in the upper ocean waters.

62. For this reason, high accuracy, ship-based full ocean depth measurements with absolute calibration from water samples, remain the 'gold standard. This is a key rationale of the GO-SHIP programme within GOOS.

63. Whilst GOOS is the primary framework for ocean observing in the open ocean, so far, it has had less traction within the Exclusive Economic Zones of many countries. Here, other drivers and national priorities come to the fore in motivating marine observations (see later).

INTERNATIONAL AND NATIONAL GOVERNANCE AND OCEAN OBSERVING

64. The United Nations Convention on the Law of the Sea (UNCLOS) divides the ocean into zones which are subject to different legal jurisdictions and regimes (Figure 9). In the water column, national jurisdictions end at the edge of Exclusive Economic Zones (EEZ) (Figure 10), 200 nautical miles from the coast or other defined baseline. Jurisdiction over the seafloor and sub-sea floor can extend to the edge of the continental shelf and claims for limited extensions are possible on demonstration of a contiguous continental shelf. Beyond these limits the High Seas (water column) and the Area (seafloor and sub-sea floor) are beyond national jurisdiction and subject to UNCLOS and any other international agreements to which States may be party.

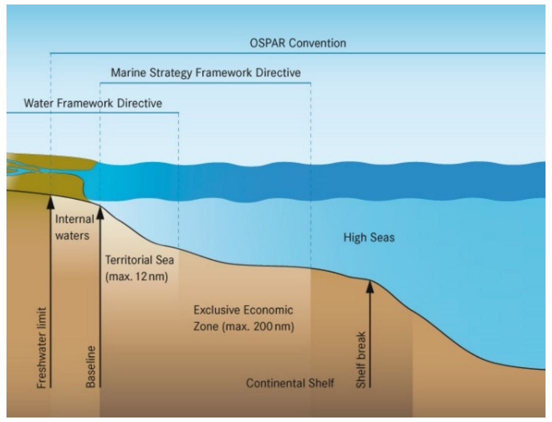


Figure 9: Jurisdictional zones of the United Nations Convention on the Law of the Sea, the OSPAR Convention, the EU Water Framework Directive and the EU Marine Strategy Framework Directive (OSPAR 2010).

The jurisdictional rights of coastal states over the water column extend up to 200 nautical miles (nm) from the baseline. Their jurisdictional rights over the Continental Shelf, relating to the seabed and subsoil, can extend beyond 200 nm. The area beyond national jurisdiction is 60% of the entire ocean area.

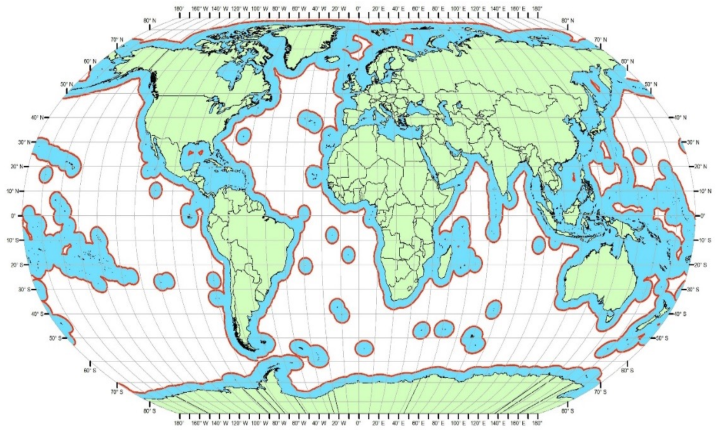


Figure 10: Map showing 200 nautical mile limits of national jurisdiction (Evans, A.)

Red lines are the 200M limits, blue areas are within national jurisdictions, white areas are beyond national jurisdiction. White areas include observations funded by research and weather services; blue areas are mostly funded by environmental and marine research management agencies and research.

65. Several international conventions have articles that require or imply a need for ocean observations, including:

- UNCLOS contains no mandated requirement for ocean observations (except relating to
- pollution), encourages research within EEZs and provides the legal basis for undertaking scientific research within and outside EEZs.
- The World Meteorological Organisation Convention (WMO Convention) mandates that member states make meteorological observations over their jurisdictions (including EEZ)

- which include weather-related ocean variables. The mandate does not extend beyond national jurisdiction, although many advanced meteorological services make open ocean measurements, including using buoys and voluntary observing ships.
- The Convention on Biological Diversity (CBD) applies to jurisdictions of States Parties and any associated marine biodiversity monitoring would be within the EEZ.
- The UN Framework Convention on Climate Change (UNFCCC) has no current reporting requirement for ocean observations e.g., within the global stocktake (Paris Agreement) although the need to address data gaps, including in the ocean, is now recognised. e.g., at COP 27 in 2022, Draft Decision -/CP.27 'Implementation of the Global Climate Observing System' recognized the importance of Earth observation systems and long-term data records and the need to address gaps, particularly in developing countries.

66. Currently, a new internationally legally binding agreement under UNCLOS for Conservation and Sustainable Management of Marine Biodiversity in Areas Beyond National Jurisdiction (BBNJ) is being negotiated. Whilst unlikely to explicitly mandate ocean observations, future observing requirements may follow establishment of high seas marine protected areas, for example. Within national jurisdictions, there are stronger drivers to undertake sustained marine observations, closely aligned with national interests. In territorial waters and EEZs, coastal states can regulate and legislate without needing international consensus. Coastal states can take provisions from international conventions and agreements (e.g., Convention on Biological Diversity, Oslo & Paris Convention, London Convention) and enforce them through domestic regulation and legislation. Thus, the regulatory regime for managing the environment and its resources tends to be highly developed within EEZs. The governance and legal framework influencers are in Figure 11.

67. Observations are undertaken by oceanographic research institutes, meteorological agencies, environment protection, management and resource agencies (UK agencies in Appendix 2). In the USA, for example, National Oceanic and Atmospheric Administration combines functions whereas in the UK, they are spread between institutions.

68. The differing motivations and institutions funding and delivering ocean observations also partition across the different legal jurisdictions described previously (Figure 11).

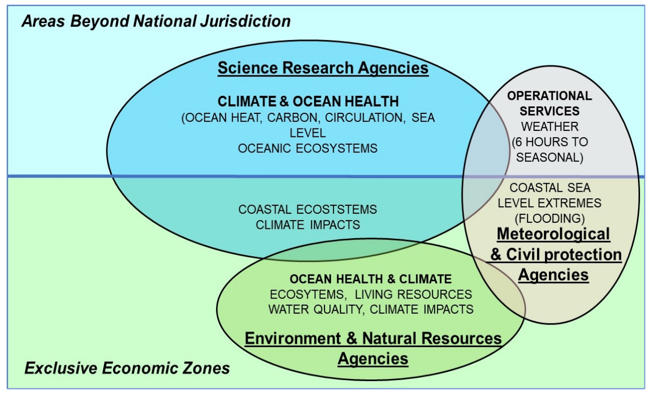


Figure 11: Who funds ocean observations, where and why?

69. When observations are motivated by marine environmental management rather than understanding processes, use of Essential Ocean Variables (EOVs e.g., GOOS) is less prominent. Instead, as exemplified by the European Marine Strategy Framework Directive (MSFD), still mirrored by the UK on leaving the European Union, the approach to monitoring is in three steps:

- Articulation of what the policy intends to achieve - in the case of MSFD, Good Environmental Status (GES) for Europe's seas;
- high level 'descriptors' of what achievement of GES will mean, are agreed;
- specific 'indicators' of progress against these descriptors are agreed.

70. Some EOV's, which are scientific parameters of the state of the ocean system and its rates of change, may be useful to monitor 'indicators', but EOVs are not the starting point.

71. Most observations, conducted beyond national jurisdictions, are funded for scientific research. Meteorological services also undertake observations in the open ocean, but these are mainly for weather related, physical upper-ocean

variables to support weather forecasting. Thus, almost all biogeochemical and ecological observations, in the open ocean beyond national jurisdiction, are funded for scientific research purposes. Moreover, climate measurements, made by meteorological services, tend to result from continuous data collection for weather services.

72. Regardless of motivation, there are common features in the decision-making cycles, that depend on data and information from systematic sustained observations (Figure 12).

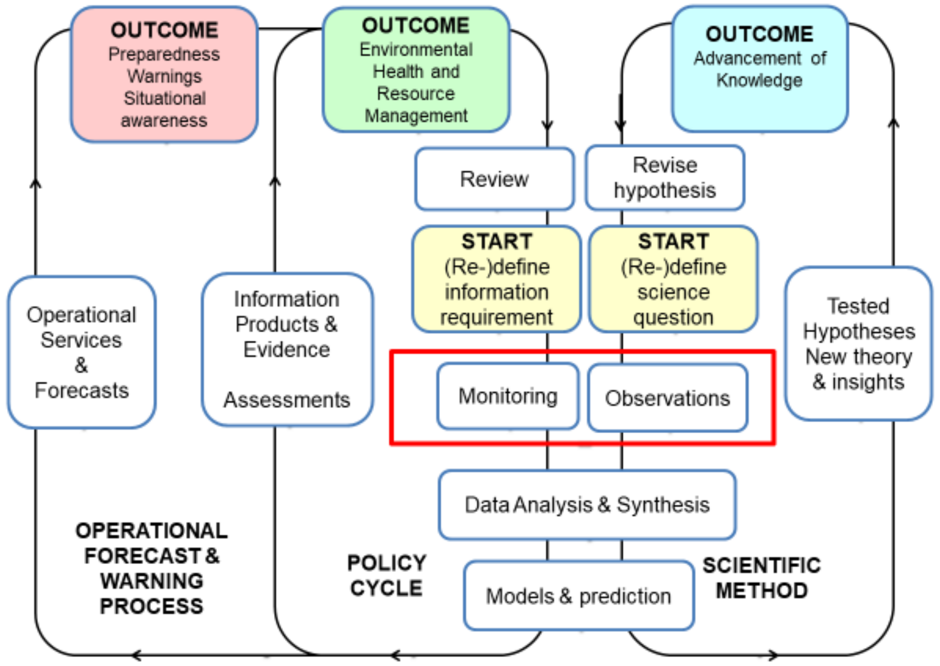


Figure 12: The role of sustained ocean observations and monitoring at the foundation of 'added value cycles'.

73. Greater cooperation between differently motivated funders of observations would be beneficial, where shared in-water observing infrastructures could serve multiple stakeholders (e.g., red box in Figure 12), however, despite some good examples of multi-agency sharing of funding, there are barriers to achieving this, including:

- financial commitments that extend beyond normal government department time frames;
- processes prohibit one government department subsidising activities that are primarily the mandate of another;
- funding constraints that expansion of marine observing can only be achieved by re-prioritising other observing that is already high priority.
- data accuracy and quality for different purposes may not be compatible (e.g., none of the UK's mainland operational tide gauges operated for flood warning are currently producing data to GLOSS standards for the global monthly mean sea level data base).

THE ROLE OF THE UK

74. The UK supports global- and regional-scale sustained ocean observations. Government has the ambition to be a 'global science superpower' (e.g., UK R&D Roadmap 2020, Integrated Review, 2021; UKRI Strategy, 2022). UK scientific output and impact is shown in the 2017 Global Ocean Science Report which shows that the UK is a major ocean science player (Figure 13 shows the UK is disproportionately large when its map is scaled by ocean science research output).

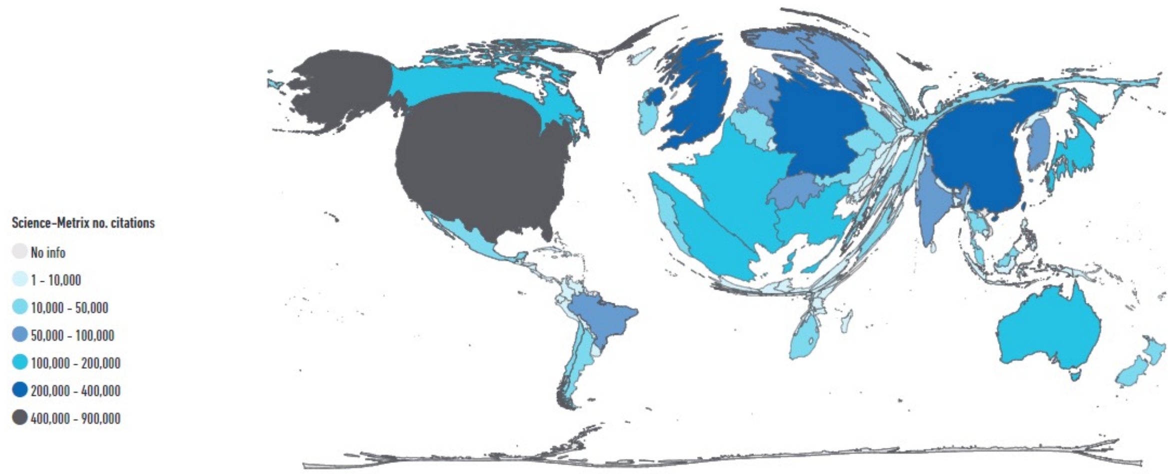


Figure 13: Ocean science citations scaled as country size (Global Ocean Science Report, IOC-UNESCO, 2017)

75. The UK has several natural advantages which lead to this position including:

- a maritime nation with access to the ocean and islands
- a diverse and healthy research ecosystem
- a track record of having sustained some of the world's longest duration data sets,
- superb large research infrastructures
- strong technological innovation capabilities.

76. To be a global science superpower requires not only the traditional metrics of scientific excellence (Figure 13) but also the ability to contribute to shared international endeavours, such as sustaining and developing global ocean observing infrastructure. The UK can contribute:

- observations where it has scientific, technical and research infrastructure capabilities e.g., global-class research ships;
- access to data which can fill gaps in global systematic data coverage.
- a fair and reasonable share of effort to major, multi-national ocean sensing endeavours.

TECHNOLOGICAL INNOVATIONS AND VISION

77. Future observing systems will need to find solutions that maximise benefit without adding to the environmental footprint and will need to adapt to the demands of a changing digital environment. The Net Zero agenda includes reducing net emissions from climate-related science itself, including ocean observing.

78. Rapid transformation of ocean observing systems requires review of traditional capability and the implications of change for the community, policy, regulation and the networks of suppliers, support workers and users of observing systems. The Net Zero Oceanographic Capability (NOC *et al.* 2021) report outlines these challenges. The ambition is to contribute to technology-enabled expansion of global ocean observations without needing more global, fossil-fuel-burning research vessels. Transitioning to clean-powered autonomous sensing platforms and replacing end of life research vessels with low carbon and zero emissions vessels will be part of the strategy.

79. The UKRI-NERC Digital Strategy 2021-2030 (NERC 2021) is a roadmap for development of digital environments that embrace new observing system capabilities.

80. Future observing systems will require the following components:

- **Part of the data ecosystem:** observing system infrastructures should be considered within the data ecosystem and user requirements that they support. This requires consideration of stakeholders and will need enhanced, integrated networks of sensors that measure a range of physical, chemical and biological processes.
- **Contributing to the Blue Economy:** To transition to a sustainable blue economy, observing systems will need to collect environmental, economic and social data.
- **Adopting greener platforms and vessels:** Meeting net zero carbon emission policies will require step changes in the design and fuelling of research ships and the capability and control of autonomous vehicles, floats and fixed platforms.
- **Improved sensor capability and endurance:** To meet requirements for multi-disciplinary, autonomous capability, with the potential for full ocean coverage, requires new sensor capability and endurance to be accepted by the community.
- **Collaboration to maximise effort and impact:** Ships and other platforms should be prioritised to encourage collaborative efforts to maximise the types of data collected, ensuring that data meets the FAIR principles, supporting the UKRI Sustainability Strategy and priority development areas.
- **Increased bandwidth and real-time communication:** Real-time virtual access to ships and adaptive sampling platforms opens up access for unlimited users. Providing broad bandwidth to ships will increases remote participation, enabling additional sensors and alternative fuels. Real-time delivery of high resolution, complex data via satellite networks would decrease the need for direct access for data retrieval and increase potential for operational and outreach applications, and opportunities for continuously adaptive sampling with dense sensor networks.

81. Scientists will need training to handle data from sensors that are left unattended for long periods. The challenge of sensor stability and data quality remain formidable for the ever more complex array of unattended biogeochemical sensors that may be mounted on autonomous fixed and mobile platforms. Extended parallel running, with high accuracy measurements, with absolute calibrations from seawater samples, from research ship-based measurements will remain crucial during transitions to unattended sensors.

PART TWO: THE UK OBSERVATIONS CONSIDERED

1. The following, mostly publicly funded, organisations deliver ocean and marine observations in the UK EEZ and beyond:

- **UK Department for Environment Food and Rural Affairs (Defra) funding:** Centre for Environment Fisheries & Aquaculture Sciences (Cefas); Environment Agency (EA); Natural England (NE); Channel Coastal Observatory (CCO); Food and Environmental Research Agency (FERA).
- **UK Department for Transport -** Maritime & Coastguard Agency (MCA)
- **UK Ministry of Defence -** UK Hydrographic Office (UKHO)
- **UK Department for Business Energy & Industrial Strategy (BEIS) -** Met Office and the UK Research & Innovation (UKRI) funding: National Oceanography Centre (NOC); Plymouth Marine Laboratory (PML); Scottish Association for Marine Science (SAMS); Sea Mammal Research Unit (SMRU); British Antarctic Survey (BAS) and British Geological Survey (BGS)
- **Scottish Government -** Marine Scotland Science (MSS); Scottish Environment Protection Agency (SEPA); Historic Scotland and Scottish Natural Heritage (SNH).
- **Welsh Assembly Government -** Natural Resources Wales (NRW)
- **Department of Environment Northern Ireland -** Agri-Food and Biosciences Institute Northern Ireland (AFBI).

The UK Government and Developed Administrations support marine observations, mostly within the UK Marine Area (EEZ). These are listed in Appendix 2 and summarised in Table 2.

Global Ocean Observing System Priorities	UK Exclusive Economic Zone	Beyond UK National Jurisdiction
Climate	**UKRI-NERC** **NOC, PML, SAMS, MBA** Met Office, MSS, EA, Cefas	**UKRI-NERC** **NOC, PML, SAMS, MBA** Met Office
Operational Services	Met Office (weather) EA (tide/surge flooding) UKHO seabed mapping MCA seabed mapping	Met Office (weather)
Ocean Health (Ecosystems)	**UKRI-NERC** Defra, Cefas, NE, MSS, SNH, SEPA, CCO, NRW. AFBNI, SMRU	**UKRI-NERC** **NOC, PML, SAMS, MBA**

Table 2: Principal UK funders of sustained ocean observations against the GOOS priorities.

2. Environmental science needs to diagnose and track emerging change and unexpected problems and develop solutions. Building on UKRI's health analogy, the role of systematic ocean observations is integral to both diagnosis and cure.

CURING THE SICK OCEAN

When a sick patient arrives in the hospital emergency room the very first thing that will be done before any treatment starts is they will be wired up to systems that monitor vital life signs – temperature, heart rate, blood pressure, oxygen saturation, remote scans may be taken, and intrusive samples obtained of blood and maybe other tissue. The reasons are:

- to diagnose the condition;
- inform a treatment plan;
- be alert to any unexpected changes or deterioration in condition;
- evaluate whether treatment is working and adjust accordingly.

To embark on treatment without making these vital sign observations would likely be considered medical negligence. There is only one ocean, and it is undergoing unprecedented change. In many ways, the ocean is even more complex than the human body. The ocean's anatomy textbook is incomplete and there are not multiple previous case histories to draw on.

Sustained ocean observations are essential. The purpose of ocean observations is not merely to diagnose the problem and describe it in ever greater detail – they are integral to finding responsible, viable science- and data-informed treatment pathways to recovery and cure.

SUSTAINED OCEAN OBSERVATIONS UNDER CONSIDERATION

3. Eleven UKRI-NERC funded, in situ sustained observing systems are considered in this report (Figure 14).

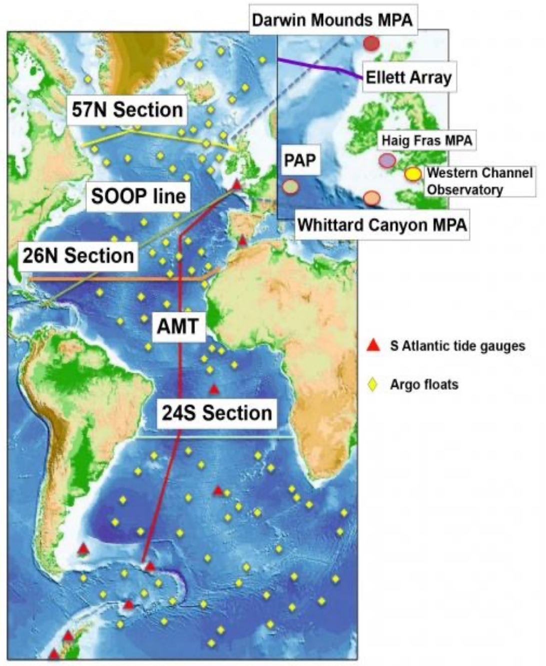


Figure 14: NERC funded UK Sustained Observations (NOC)

ATLANTIC MERIDIONAL OVERTURNING CIRCULATION

4. The AMOC (RAPID) array across the Atlantic at 26°N has observed the AMOC continuously since 2004. It is a contribution to GOOS-OceanSITES Transport Moored Arrays (TMA). It tracks trends and variability at the latitude of maximum northward heat transport and where the entire flow can be measured because part of it is confined to the Florida Strait

(Frajka-Williams *et al.* 2019. Li *et al.* 2021). The original array has been optimised after about eight years of operation using model simulations with several moorings taken out as not adding material to determination of the AMOC. It aims to understand how the AMOC works and is used internationally as a benchmark for coupled climate models (e.g., Hirschi *et al.* 2020).

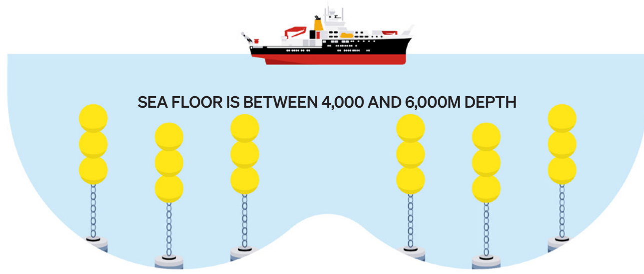


Figure 15: AMOC: Atlantic Meridional Overturning Circulation – trans-Atlantic (26ºN) moored buoy array serviced by research ship.

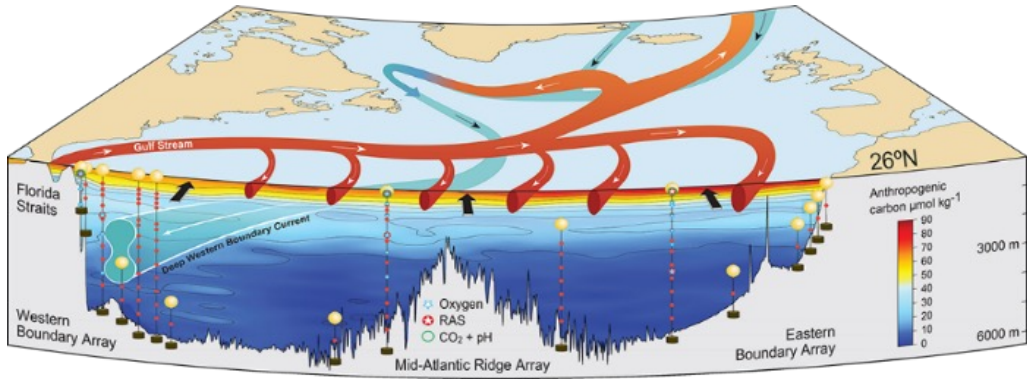


Figure 16: Schematic of the Atlantic Meridional Overturning Circulation (AMOC) with concentrations of anthropogenic carbon concentrations at 24.5°N in 2010. ABC will deploy biogeochemical sensors (oxygen, pCO2, pH) and remote access sampling (RAS) on some of the RAPID moorings, as indicated in the figure. Credit: NOC/P. Brown & V. Byfield.

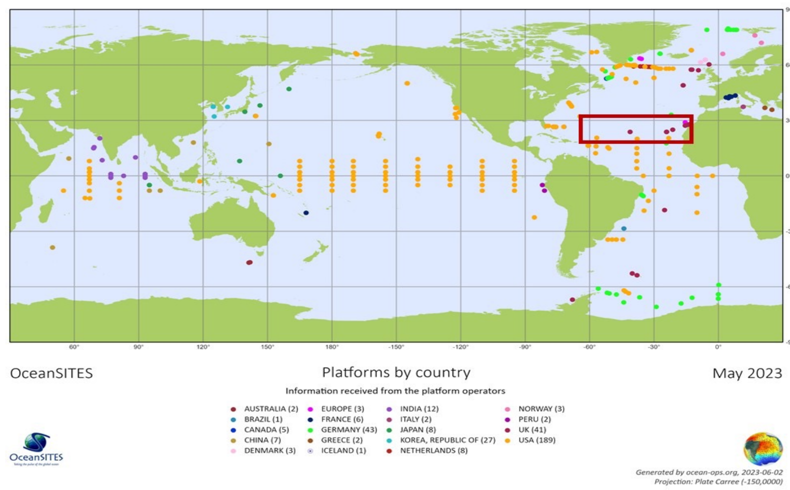


Figure 17: The global OceanSITES array which includes the UK contribution (red box) to the AMOC array at 26ºN in the eastern Atlantic in collaboration with the USA (western Atlantic). Credit: OceanSITES

THE ATLANTIC MERIDIONAL TRANSECT (AMT)

5. The AMT programme undertakes biological, chemical and physical oceanographic research during an annual voyage between the UK and the South Atlantic. Established in 1995, it enables open ocean observations through a wide latitudinal range, including the rarely sampled north and south Atlantic gyres (e.g., Aiken *et al.* 2017) and helps with forecasting and identifying trends. AMT data addresses issues such as sustainability, climate change and marine ecosystems. The research contributes to science and policy development. AMT cruises have hosted over 220 scientists, produced over 300 scientific papers and contributed to more than 75 PhD studies. It enables national and international scientific collaboration and trains the next generation.

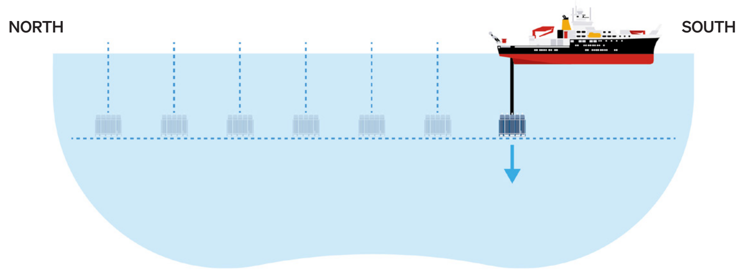


Figure 18: AMT – Atlantic Meridional Transect research ship of opportunity sampling upper 200m (UK to South Atlantic)

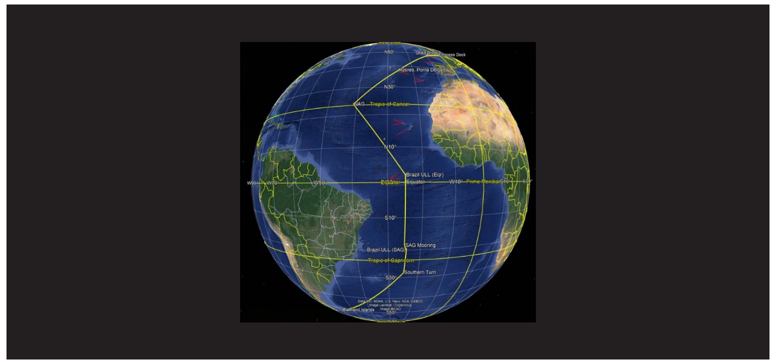


Figure 19: AMT legs undertaken on research ship passage legs to the South Atlantic (mostly polar research/supply ships. AMT 30, Plymouth Marine Laboratory

ONE ARGO (STANDARD, BIOGEOCHEMICAL (BGC) AND DEEP ARGO)

6. Globally, Argo generates 100,000 profiles of ocean temperature and salinity per year in the upper 2,000m with the array expanded since the first floats were deployed in 2,000 with the intention of maintaining over 3,000 floats in operation at any one time. It is the key data source for ocean heat uptake (von Schuckmann *et al.* 2020). The UK has the 5th largest number of active floats contributing to GOOS-Argo– around 4% of the float array and its efforts are focussed in the North and South Atlantic and Southern Ocean. The array is being diversified to include a subset of floats profiling to full ocean depth (Deep Argo) and a subset with biogeochemical sensors (BGC Argo). The global programme has produced 5,599 papers since 1998 of which the UK has published about 6%.

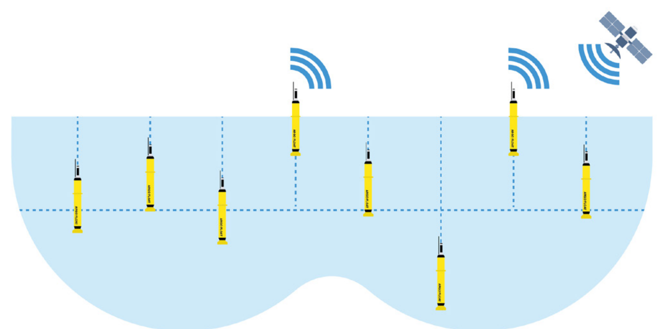


Figure 20: ONE ARGO: Standard Argo profiling floats (temperature, salinity) in upper 2,000m with Biogeochemical Argo and Deep Argo (6,000m) being added.

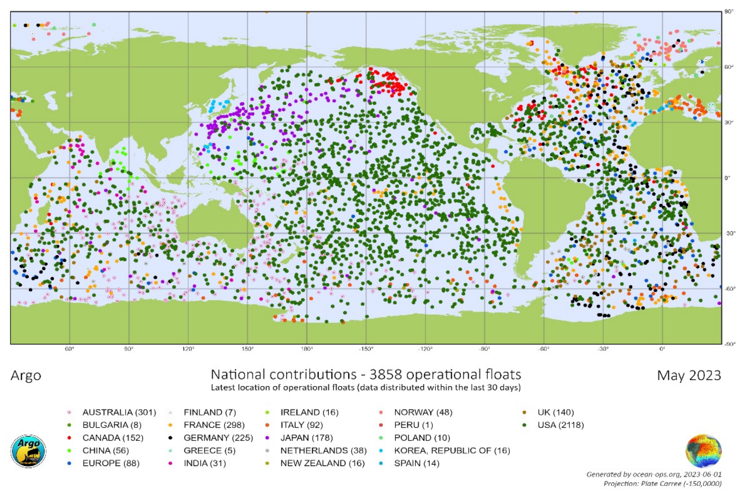


Figure 21: The global array of Argo profiling floats – the majority are standard Argo (temperature and salinity to 2,000m depth) with biogeochemical floats (currently about 300) and Deep Argo (very few) being added/substituted. Credit: Argo (2023)

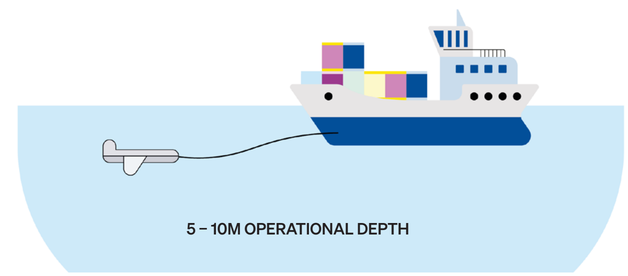


Figure 22: CPR - Continuous Plankton Recorder – North Atlantic basin surface phytoplankton and zooplankton surveys

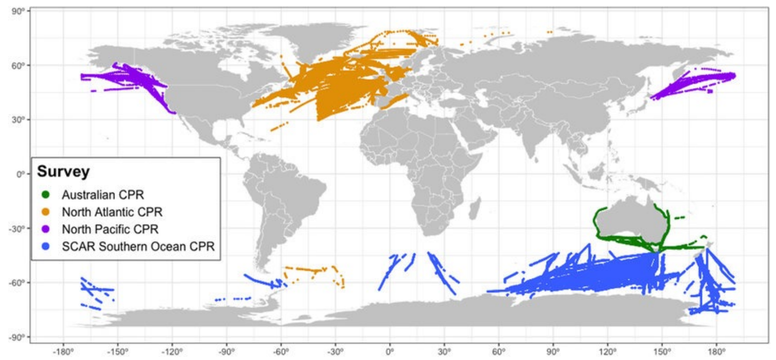


Figure 23: The UK contribution to Global Alliance of CPR surveys is the North Atlantic (the longest records) Campbell (2021)

THE CONTINUOUS PLANTON RECORDER (CPR)

7. The CPR monitors phytoplankton and zooplankton in the top 20m of the ocean from plankton recorders towed mainly by commercial vessels with the UK contribution mostly in the North Atlantic and the longest records going back over 90 years. The dataset comprises a uniquely extensive record of marine biodiversity covering ~1000 taxa over multi-decadal periods.

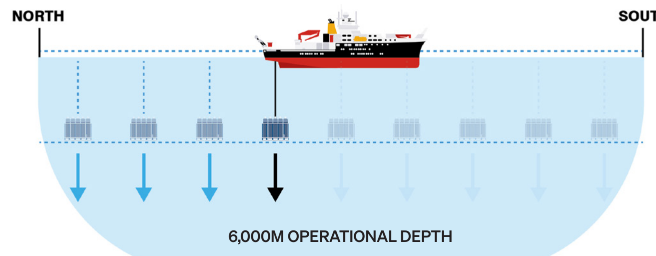


Figure 24: GO-SHIP – full ocean depth, trans-basin hydrographic sections with carbon

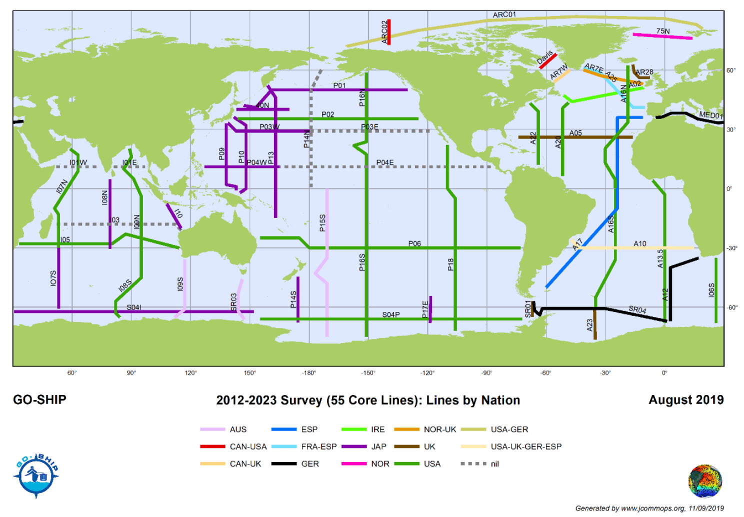


Figure 25: The GO-SHIP global array of core lines with UK contributions in the Atlantic and Southern Oceans (Credit: OceanOPS (2019))

GO-SHIP REPEAT SECTIONS (24°S, 26°N, 57°N AND DRAKE PASSAGE

8. The GOOS-GO-SHIP (Global Ocean Ship Based Hydrographic Investigation Program) is developing a globally coordinated network of sustained, repeated trans-oceanic hydrographic sections as part of the global ocean/climate observing system. Some transects sampled are repeated once per decade, every five years and some annually. It is the only data source for the global inventory of carbon including the deep-sea inorganic carbon sink.

ELLETT ARRAY (GLIDERS, MOORINGS AND CTD)

9. The Ellett Array measures the ocean to the west of the UK in a region of warm surface poleward water inflow and downstream of overflow of sub-Arctic waters into the subtropical basins. The CTD element has been repeated since the 1970s. It looks at water mass properties and how and why the currents, temperature and salinity have changed over the past few decades. It is a UKRI contribution to the international OSNAP project (Overturning in the Sub Polar North Atlantic) that is measuring the Atlantic Meridional Overturning Circulation (AMOC) in the subpolar North Atlantic (where the sinking to form North Atlantic deep waters occurs).

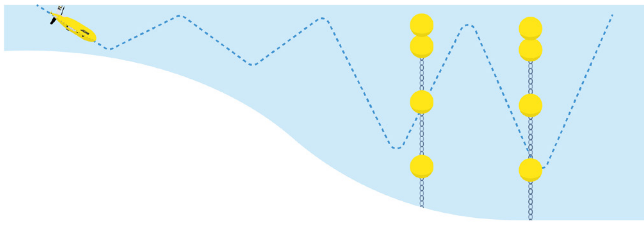


Figure 26: Ellett Array – glider surveys and ship-serviced moored buoy arrays in eastern subpolar North Atlantic

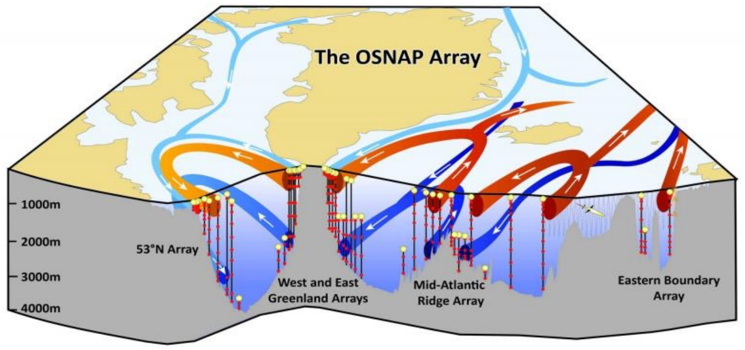


Figure 27: The Ellett Array presently represents the UK contribution of eastern part of the OSNAP multi-national subpolar North Atlantic array. Credit: Penny Holliday, (2015)

PORCUPINE ABYSSAL PLAIN (PAP) DEEP SEA OBSERVATORY

10. The Porcupine Abyssal Plain Sustained Observatory is a sustained, multidisciplinary fixed-location observatory in the Northeast Atlantic in water depth 4,850m. It is a contribution to GOOS-OceanSITES. For over 20 years since 1985, the observatory has provided key time series datasets for analysing the effect of climate change on the open ocean and deep-sea ecosystems. It measures the flux of organic carbon from sea surface to the sea flow (biological carbon pump) and the seabed observations is one of only two such sites on abyssal plains where benthic-pelagic coupling can be investigated as the seabed responds to intermittent bursts of 'marine' snow raining from the surface ocean (e.g. Hartman *et al.* 2021).

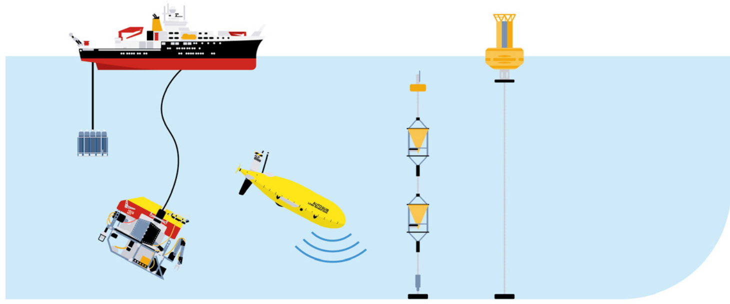


Figure 28: PAP: Porcupine Abyssal Plain Deep-sea Observatory 5,800m downward carbon flux

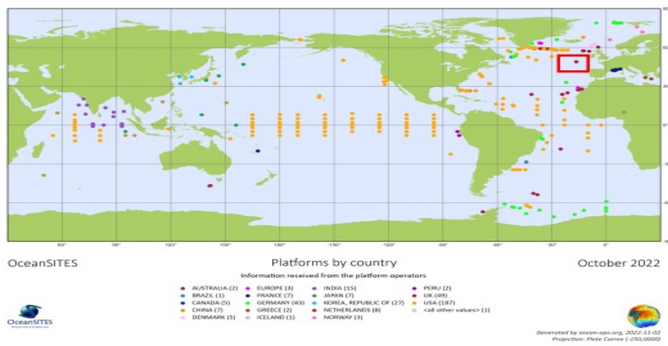


Figure 29: The Global Ocean sites network – PAP is one of a small number of interdisciplinary mooring sites (biogeochemistry, carbon, ecology) contributing to Ocean Sites (Credit: Ocean-ops.org, (2022)

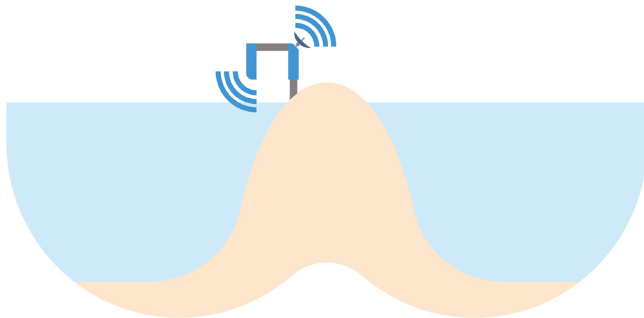


Figure 30: GLOSS: Global Sea Level Observing System – tide gauges on oceanic islands in South Atlantic and Antarctica

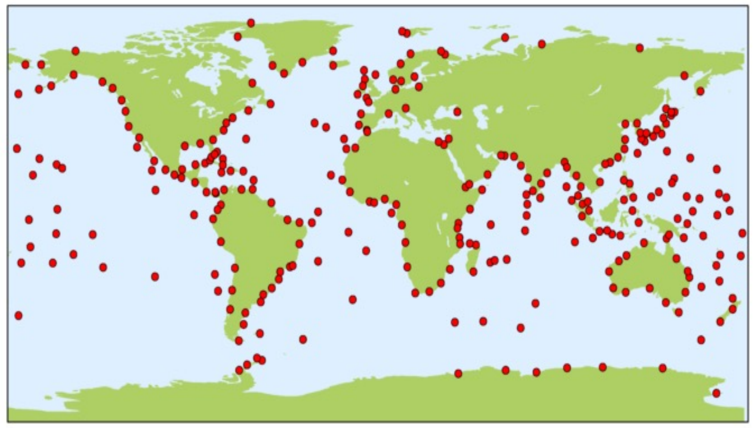


Figure 31: The GLOSS Core Network of coastal and oceanic island tide gauges – the UK contributions are around UK coast (Environment Agency) and South Atlantic oceanic islands and Antarctica (UKRI-NERC) Credit: PSMSL

THE GLOBAL SEA LEVEL OBSERVING SYSTEM (GLOSS) INTERNATIONAL COASTAL AND ISLAND TIDE GAUGE NETWORK

11. Island tide gauges on South Atlantic islands and Antarctica (Overseas Territories) obtain mean sea level measurements for calibration of satellite altimeters and where islands are representative of oceanic sea level signatures uncontaminated by land and shallow water effects. They provide time series of relative sea level (to land), absolute sea level (where land movement is measured), water temperature and air pressure for understanding long-term sea-level trends and variability and extremes on timescales, including evaluation of seiches, storm surges, tides and seasonal patterns and to complement satellite altimetry which has lower frequency of sampling. This contributes to the GOOS-GLOSS (Global Sea Level Observing System) programme. Data from GLOSS is central to the IPCC State of the Climate Reports (e.g. IPCC, 2021, Chapter 9, Jevrejeva *et al.* 2019, Jevrejeva *et al.* 2020).

WESTERN CHANNEL OBSERVATORY (WCO)

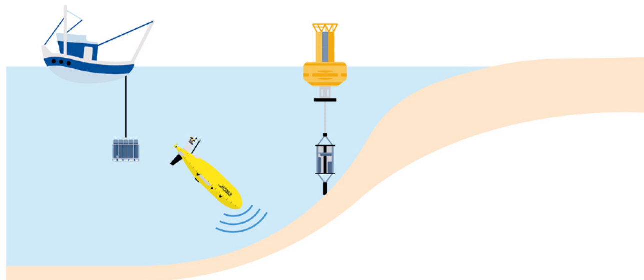


Figure 32: Western Channel Observatory – two fixed sites in coastal waters off Plymouth – delivering ecological and biogeochemical repeat and continuous observations.

12. The Western Channel Observatory (WCO) is an oceanographic time-series and marine biodiversity reference site in the Western English Channel. (e.g. Smyth *et al.* 2015). Data are collected at coastal station L4 and open shelf station E1 by the Plymouth Marine Laboratory and the Marine Biological Association (MBA). These measurements are complemented by ecosystem modelling and satellite remote sensing science. The WCO measures parameters important to the functioning of the marine ecosystem such as light, temperature, salinity and nutrients. L4 has some of the longest time-series in the world for zooplankton and phytoplankton, and fish trawls have been made by the MBA for a century. L4 has UN Ocean Decade-recognised biomolecular observations and E1 has a hydrographic series dating from 1903. These series are complemented by measurements made at moorings at both stations. Parameters measured at WCO contribute to the Global Ocean Acidification Network, GOAN (Tilbrook *et al.* 2019).

Figure 33: Western Channel Observatory sampling stations (WCO 2022)

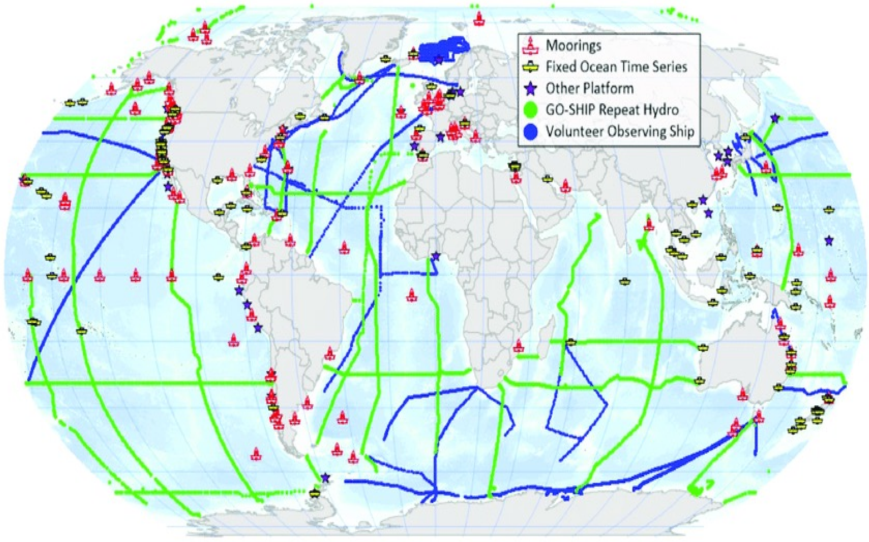


Figure 34: One element of the WCO measures ocean acidification and is a UK contribution to the Global Ocean Acidification Network (GOAN) which includes components from OceanSITES, GO-SHIP, Ships of Opportunity (SOO-C) as well as contributing coastal sites like the WCO (Credit: Tilbrook, B; et al. 2019)

SHIP OF OPPORTUNITY SURFACE UNDERWAY MEASUREMENTS INCLUDING SURFACE METEOROLOGY, SURFACE TEMPERATURES AND PCO_2

13. Observations of nutrients, Carbon, CO_2 and salinity are collected between the UK and the Bahamas. These observations contribute to the Integrated Carbon Observation System.

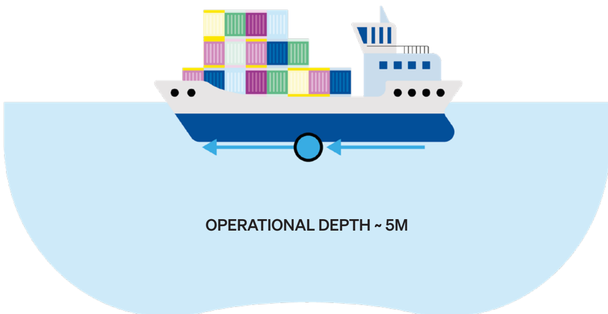


Figure 35: SOO-C: Commercial Ship of Opportunity trans-Atlantic ocean surface carbon measurements

MARINE PROTECTED AREAS REPEAT SURVEY

14. The impact of human activity is extensive and increasing as countries develop their blue economies. Changes in habitats across different domains are observed at the Haig Fras, Darwin Mound and the Whittard Canyon Marine Conservation Zones (e.g. Benoist *et al.* 2019; Amaro *et al.* 2016).

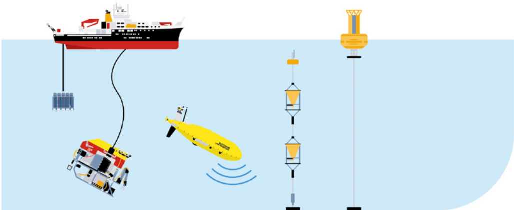


Figure 36: MPA: Repeat Marine Protected Areas: seabed ecological sampling Darwin Mounds, Whittard Canyon (deep) and Haig Fras (continental shelf).

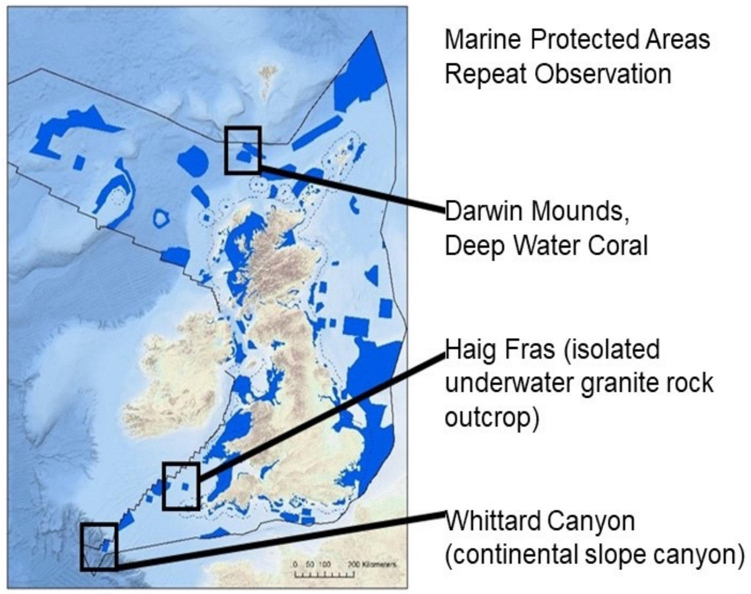


Figure 37: Map and statistics include SACs, SPAs. MCZs and NCMPAs only © JNCC 2018. UK Territorial Sea Limit. UK Exclusive Economic Zone. UK Continental Shel (Designation of Area) Order 2013. Contains UKHO data & Crown copyright. Contains EMODnet Digital Bathymetry (DTM) from EMODnet Bathymetry Consortium (2016). Contains JNCC Natural England, Scottish Natural Heritage. DEARA & Natural Resources Wales data © Copyright and database right 2018.

SUMMARY OF FEATURES OF OBSERVATIONS UNDER CONSIDERATION

15. The observations track different aspects of heat and carbon uptake and storage at basin scale and impacts on biogeographical distributions, biogeochemical properties, planktonic biomass and biodiversity (Figure 38) and are made at basin scale, mostly as part of global observing networks (GOOS, GACS). Biodiversity and habitat impacts are more localised and site-specific on account of cumulative specific impacts as well as climate change and are tracked with the continental margin and coastal ecological observing systems within the UK's EEZ (Figure 39)

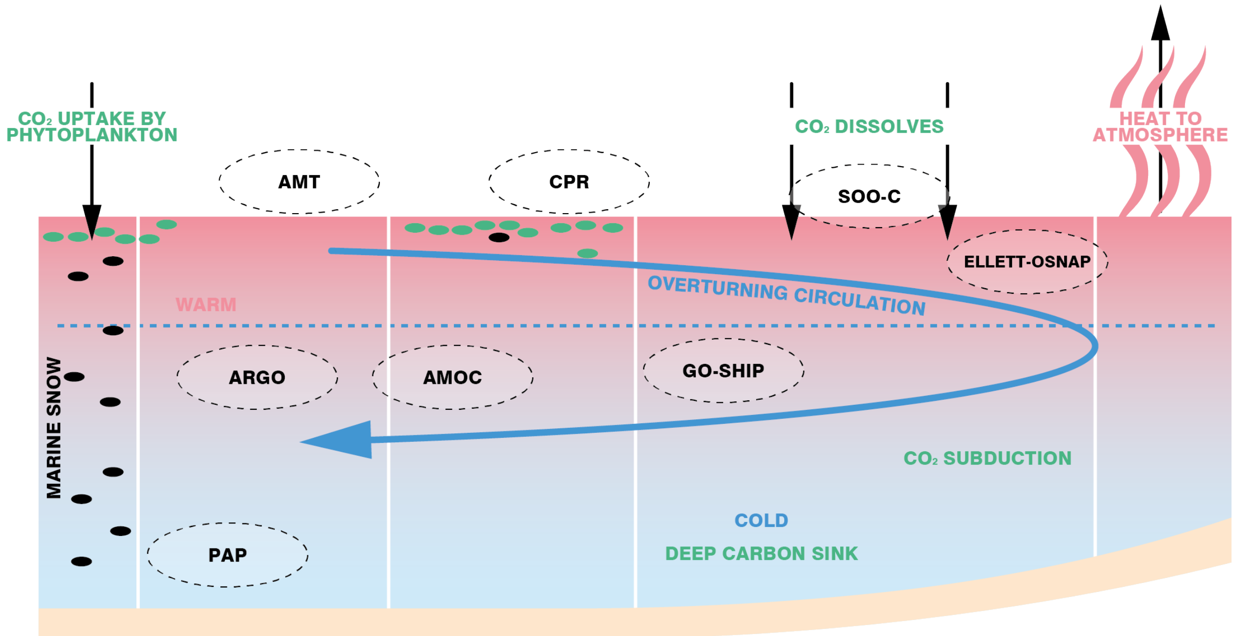


Figure 38: Basin scale sustained observations which measure heat (AMOC, ARGO, GO-SHIP, Ellett/OSNAP); carbon uptake, subduction into the deep (SOO-C, PAP, GO-SHIP, AMOC, Ellett/OSNAP); upper ocean biogeochemical/ecological changes, surface plankton biodiversity and distributional change (AMT, CPR).

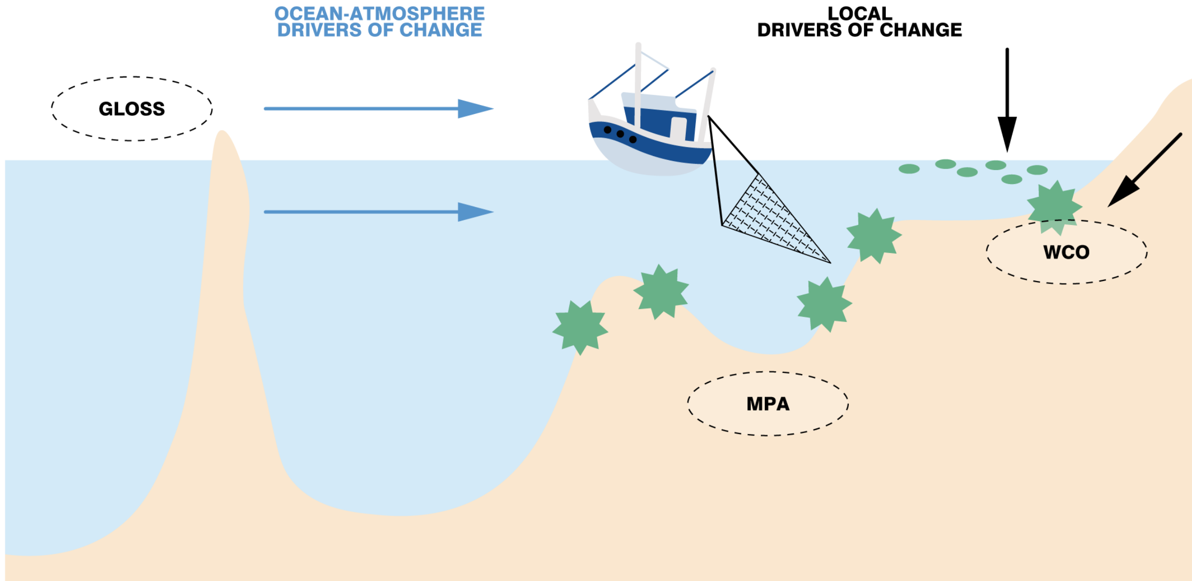


Figure 39: Measurements made at or near coasts and ocean margin. Sea level rise from remote oceanic islands and Antarctica (GLOSS); marine benthic habitats under protection at the continental margin in deep water and continental shelf that are impacted by basin-scale drivers and human impacts (MPA); near coastal characterisation of biogeochemical and ecological properties, basin-scale drives and local impacts - transitional stratification, riverine impact, local weather and localised human impacts and a test bed for experimentation, equipment demonstration and regional seas ecosystem model development and testing (WCO).

16. The main practical features of the eleven observing systems.

	AMOC	ARGO	GOSHIP	ELLETT	SOO-C	PAP	AMT	GLOSS	CPR	WCO	MPA
MAIN PLATFORM TYPES USED											
Fixed moorings	■			■		■				■	
Profiling floats		■									
Gliders				■						■	
Autonomous underwater vehicles						■					■
Large research ships	■		■	■		■					■
Opportunistic use of research ships		■					■				
Small coastal research vessels										■	
Commercial ships of opportunity					■				■		
Land-based stations								■		■	
GLOBAL OCEAN OBSERVING SYSTEM											
Defined in situ system of GOOS	■	■	■			■		■			
Global Ocean Acidification Network										■	
Global Alliance of CPR Surveys									■		
DURATION OF LONGEST ELEMENTS											
<10 years					■						■
<20 years	■										
<30years		■	■				■				
<40years						■					
40 years +				■				■	■	■	
SAMPLING FREQUENCY											
Continuous	■	■		■	■	■		■	■	■	
2 weeks										■	
6 months											
Annual							■				
Once per 5 years			■								■
SERVICING/RE-DEPLOYMENT INTERVAL											
Once per 6 months					■				■	■	
Once per year				■		■	■				
Once per 2 years	■							■			
Once per 5 years		■	■								■
SPACE-SCALE OF UK SYSTEM											
Basin-wide	■	■	■		■		■		■		
Large sub-basin or representative				■		■		■			
Localised/coastal										■	■
VARIABLES MEASURED											
'Platform' for multiple science projects						■	■			■	■
'Platform' for technology demonstration						■				■	■
Targeted core measurements	■	■	■	■	■	■	■	■	■	■	■
COST TO UKRI-NERC											
High (> 200k/year)	■					■	■			■	■
Medium		■		■							
Low (<50k/year)			■		■				■		
ANNUALISED CARBON FOOTPRINT											
High large research ships, frequent	■					■					
Medium - large ships, infrequent; small vessels frequent			■	■			■			■	■
Low - small vessels in frequent, vessels of opportunity, no vessels		■			■			■	■		

Table 3: Main features of in situ sustained observing systems under considerations

17. The ways that observation systems contribute to measuring different aspects of the large basin-scale climate drivers and the ecological responses and other impacts are shown in Table 4.

HIGH LEVEL SCIENTIFIC ISSUES ADDRESSED BY THE SUSTAINED OBSERVATIONS UNDER CONSIDERATION	AMOC	ARGO	GOSHIP	ELLETT	SOO-C	PAP	AMT	GLOSS	CPR		WCO	MPA
Ocean basin-wide and global heat content	■	■	■	■								
Ocean basin-wide heat redistribution	■	■	■	■								
Ocean global and basin-wide deep carbon reservoir			■									
Carbon uptake into surface ocean					■	■	■					
Carbon flux into deep ocean	■					■						
Global and basin-wide sea level rise								■				
Ocean acidification										■	■	
Hydrological cycle	■	■	■	■								
Upper ocean basin-wide biogeochemistry		■	■				■					
Surface plankton basin-wide distribution									■			
Abyssal plain benthic-pelagic coupling						■						
Localised ecological impacts and responses										■	■	■

Table 4: Sustained observations primarily support the science relating to climate drivers and biodiversity impacts.

PART THREE: APPROACH TO PRIORITISATION

1. A framework for strategic prioritisation is suggested, determined by three considerations in relation to the 'value chain' of ocean observations (Figure 40).

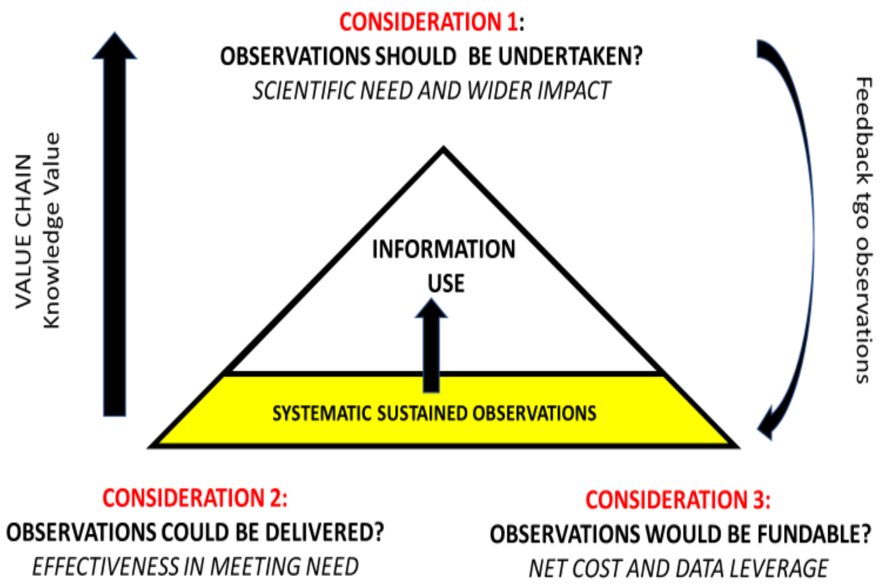


Figure 40: Framing the considerations for developing criteria for investment in sustained ocean observations needed for scientific research (Ed Hill, NOC)

CONSIDERATION ONE: SCIENTIFIC NEED

2. Do the observations have scientific value; do they need to be sustained?
    - **Primary purpose** – will it advance knowledge and understanding?
    - **Science questions** - are well posed scientific questions being enabled?
    - **Scientific significance** - is the science of international significance?
    - **Timeliness** - is the need timely in supporting important scientific questions?
    - **Data availability** – will the data be accessible in a timely manner and widely used?
    - **Impact** - does the information and science enabled have significant impact?
    - **Need for UK contribution** – what are the needs for a UK contribution?

CONSIDERATION TWO: EFFECTIVENESS IN MEETING NEED

3. Can the observations be made effectively?
    - **Methodology** - is systematic, sustained observation the best method?
    - **Space-time scales** - are relevant space-scales adequately addressed?
    - **Scalability** - could this be scaled if necessary and still make a viable contribution?
    - **Uniqueness** – can this observation only by made by the UK?
    - **Capabilities** – are the capabilities sufficient to make these observations?
    - **Innovation** - What is the likelihood, over the next five years, to increase data value or undertake observing more cost effectively by technology or innovation?

CONSIDERATION THREE: NET COST TO UKRI-NERC

4. Is the cost of the observations affordable compared to others, in terms of need and value?
    - **Relative cost tensioning** - Is the cost proportionate compared to others?
    - **Co-funding** - Is there a financial contribution by others where a significant part of the observations is meeting a primary purpose other than science?
    - **Leverage** – how significant is the data captured by other contributors?
5. Prioritisation of investments can be made using matrices (Figure 41) which presume that if the primary motivation for funding observations is advancement of science, then observations with:
    - high scientific value taking precedence over low despite higher societal impact;
    - high overall value taking precedence over low despite greater effectiveness in delivery;
    - high funding prospect, lower net cost take priority over high funding prospect, higher cost.
6. UKRI-NERC requested that no account be taken of costs so only 1 and 2 are considered.
7. This approach could be adapted for others where their primary motivation may be other than scientific e.g., support for operational services.
8. In considering observations, there are some common, but spurious, justifications (Box 1).

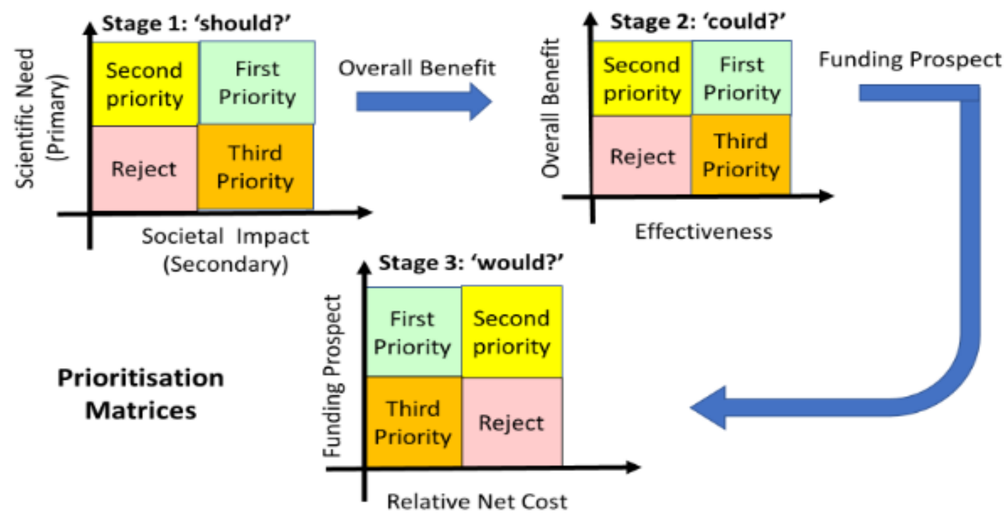


Figure 41: Stages in prioritisation of observations

BOX 1: COMMON BUT SPURIOUS JUSTIFICATIONS FOR SUSTAINED OCEAN OBSERVATIONS

1. **A sustained observation is worth making because if measured long enough something of interest will be found.** This statement could justify measuring almost anything anywhere.
2. **Observations that have been carried out for a long time are priority.** Observations may not be useful if unrepresentative of the space-time scales of phenomena under investigation.
3. **Long observing programmes should be continued to justify the resources spend over previous years.** This is the 'sunk cost fallacy' so not a justification.
4. **The method of observation should not change because data consistency will be lost.** There is almost no environmental data series where innovation in technology or method has not changed.
5. **Sustained observations are essential because they will benefit in managing natural resources, the environment, risks and hazards.** Possibly true but if the purpose is resource/environmental management, the variables measured must link to indicators or hazard indices used by the stakeholders responsible, otherwise, there is no assurance that what is measured will be beneficial.
6. **All sustained observations should have an expectation of being operated indefinitely.** Though appropriate in some cases, such as weather forecasting, scientifically motivated observations are inherently time limited and subject to review as to the need in relation new knowledge and understanding needed. Initially scientifically motivated observations could transition into support for and operational service or other need.
7. **By terminating an observation, the UK reputation will be damaged internationally.** Possibly, but depends on the observation and reason for termination. The ones that carry the most significant reputational risk are those for which a large number of countries contribute, and the UK withdraws leaving less wealthy of capable countries to pick up the load. The other is where the UK contribution makes a globally significant scientific contribution and withdraws without strong scientific justification.

PART FOUR: CONSULTATION FINDINGS

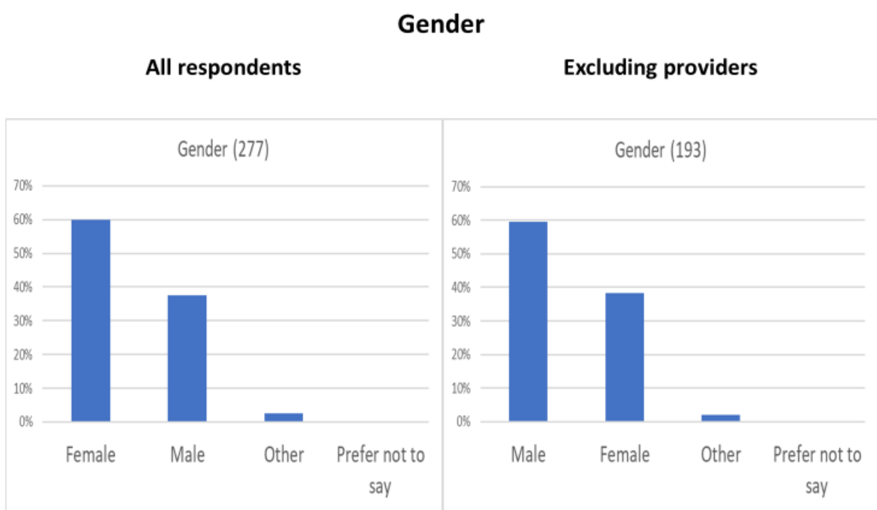
1. Three consultations were used to inform the prioritisation of investments UK ocean observations:
   - an on-line survey (Appendix 3) which received 189 responses;
   - a discussion at the AGM of the NOC Association;
   - a panel of UK and international experts in sustained ocean observations.

ONLINE SURVEY

2. The survey asked about background and affiliation, views on sustained ocean observations and on the eleven systems under consideration.
3. The National Oceanography Centre, Plymouth Marine Laboratory, Scottish Association for Marine Science and the Marine Biological Association are referred to as 'providers' of observations. To avoid possible bias in favour of particular systems, responses were presented showing both all and excluding those from 'provider' organisations. In the event, there are few material differences in responses that would affect overall conclusions.
4. Numbers refer to all respondents; the equivalent, when 'providers' are excluded, is in brackets.
5. Respondents could either strongly agree; agree; neither agree nor disagree; disagree or strongly disagree. The graphs show percentages of respondents who strongly agreed or agreed with the prioritisation. Percentages are ranked with the highest percentages at the bottom of the graphs.

DEMOGRAPHY

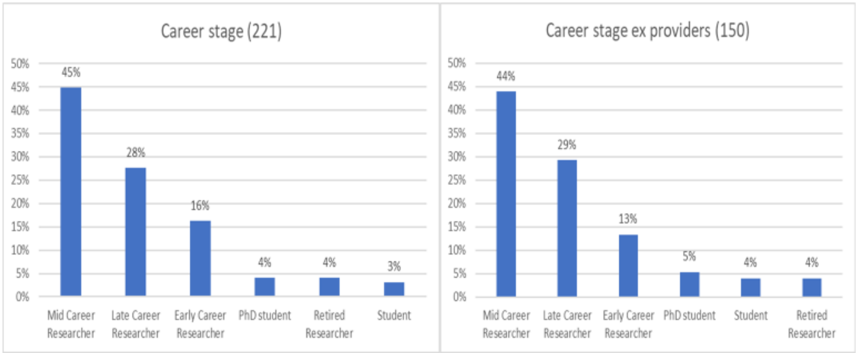
6. Some 60% of respondents (38%) identified as female. This is the single largest difference between including and excluding provider institutions where the latter show significant numbers of women responding. Worldwide, some of the most prominent leaders and advocates of sustained ocean observing are women.



7. Some 61% (57%) identified as early- and mid-career with 54% (54%) under the age of 50.

Career Stage

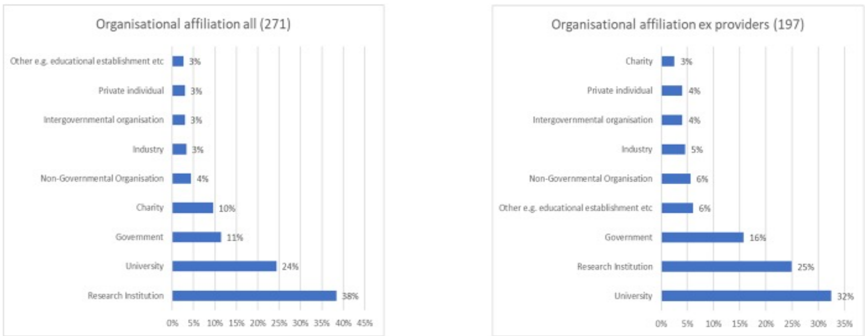
All respondents **Excluding providers**



8. Organisational affiliation was varied with 62% (57%) affiliated universities and research institutions.

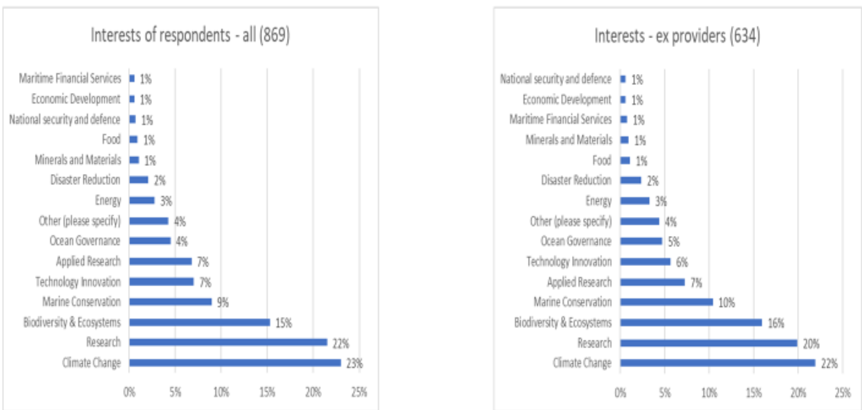
Organisational affiliation

All respondents **Excluding providers**



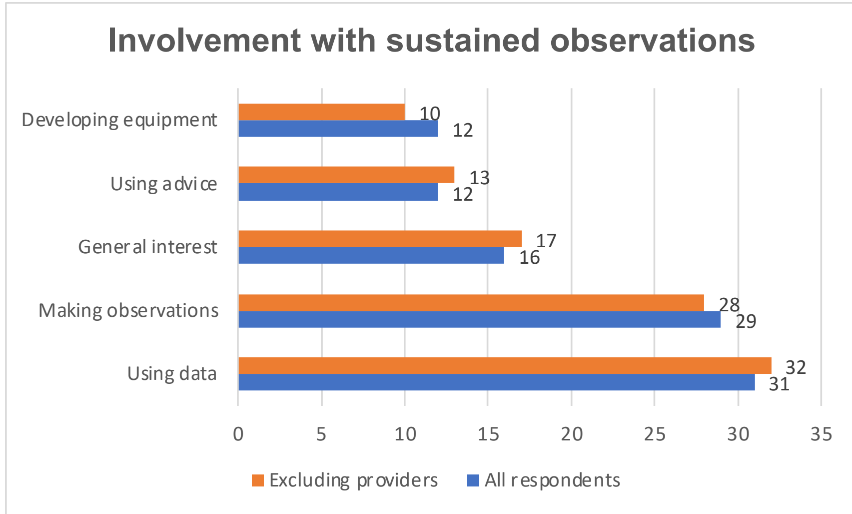
Interests of respondents

All respondents **Excluding providers**

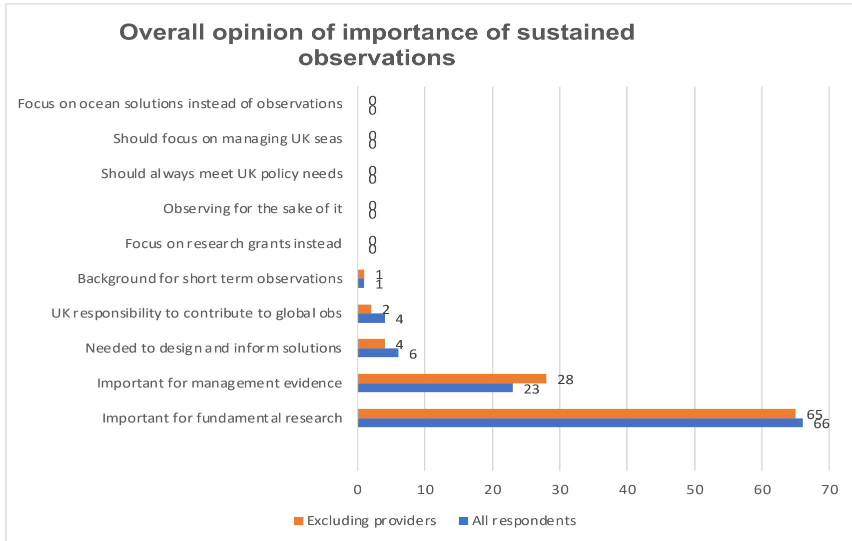


OVERALL VIEWS ON SUSTAINED OBSERVATIONS

9. Some 61% (60%) of respondents make and/or use data from sustained observations.



10. The majority saw the sustained observations as important for advancing fundamental research - 66% (65%) and or supporting management of the marine environment - 23% (38%).

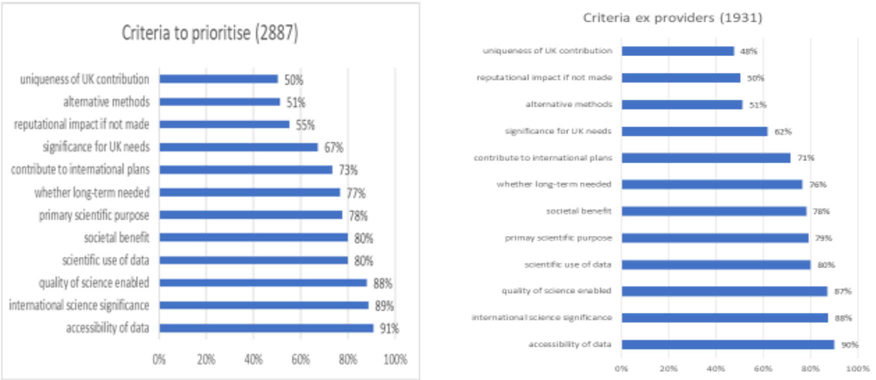


11. Respondents could include the view that sustained observations are 'observing for its own sake' or that efforts should focus on 'ocean solutions rather than observing' but these were not selected. There was almost no support for this opinion. Whilst this may reflect the demography of respondents, it more likely reflects the view that sustained ocean observations play an important role in supplying evidence that supports ocean actions, e.g., marine management.

12. Before respondents were asked their view, views were sought on the criteria that UKRI-NERC should consider regarding funding. Responses below are the percentages of those who said they 'agree' or 'strongly agree' with the propositions provided.

Criteria that should be used by UKRI in prioritising sustained observations

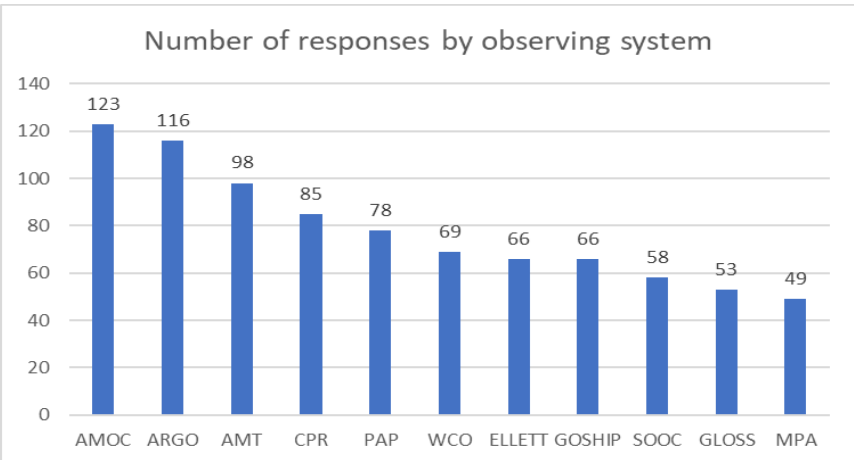
All respondents **Excluding providers**

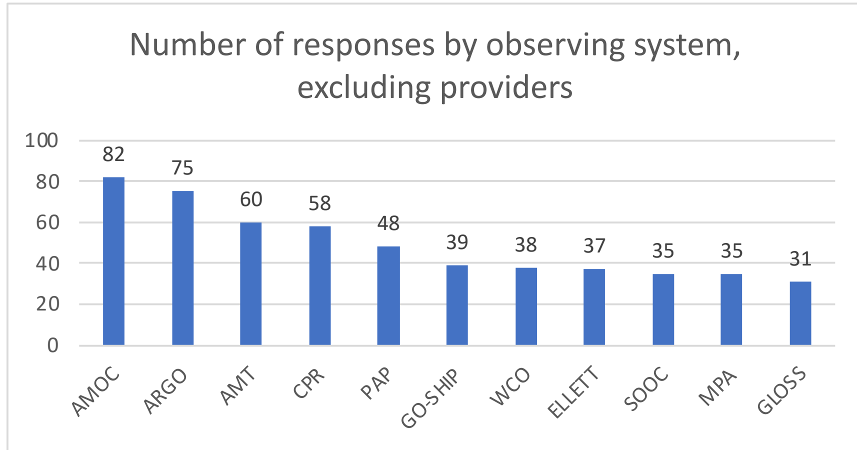


13. The top response at 91% (90%) was 'accessibility of data' with the 'quality of science enabled' and the 'international scientific significance' in the top three responses followed by 'wider international scientific use of data'. Societal benefit was rated highly in 80% (78%) of responses. The scientific value of sustained ocean observations is the prominent consideration for respondents and consistent with criteria that UKRI-NERC indeed apply.

OPINIONS ON INDIVIDUAL OBSERVING SYSTEMS

14. The number of respondents for each observing system varied, probably reflecting the scale, visibility and levels of interest. Although it was possible for respondents to skip observing systems in the survey, it is possible there could have been 'survey fatigue' for those who worked through the survey in the order the observing systems came up which was: AMOC, AMT, Argo, CPR, GO-SHIP, ELLETT, PAP, GLOSS, WCO, SOOC, MPA) although numbers of responses do not exactly follow this sequence.



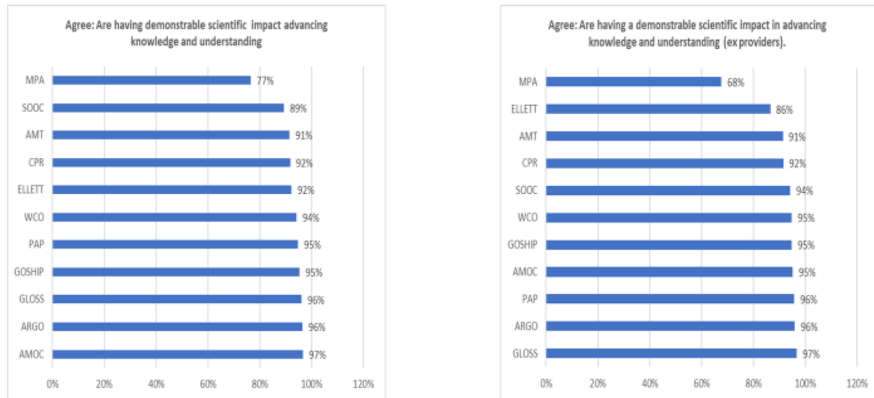


HEADLINE VIEWS

15. Overwhelmingly, all eleven sustained ocean observing systems - where UKRI-NERC wholly or partly contributes to their capital or operating costs - were considered scientifically important and there was a strong view that all should be continued with almost no support for discontinuation of any (percentages all under 4% of discontinuation).

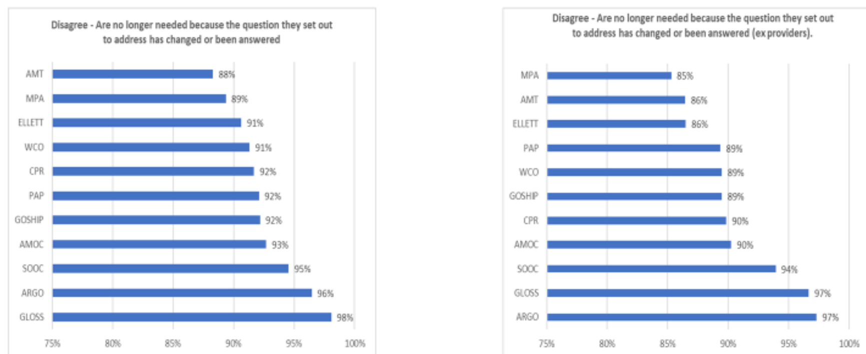
Demonstrable scientific impact in advancing knowledge and understanding

All respondents **Excluding providers**



Disagree that no longer needed as science questions addressed

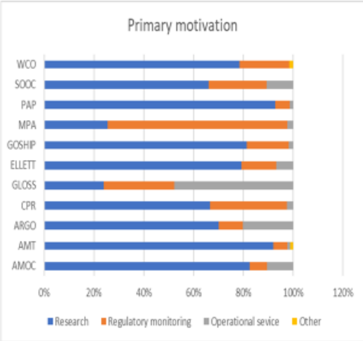
All respondents **Excluding providers**

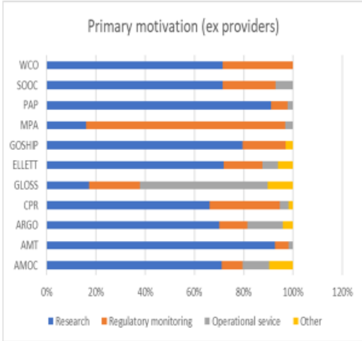


16. Most observations were considered to be primarily motivated by a scientific rationale and therefore appropriate for funding by UKRI-NERC.

Primary motivation for observations

All respondents **Excluding providers**





17. Two exceptions regarding motivation stand out (MPA and GLOSS). Comments offered below:

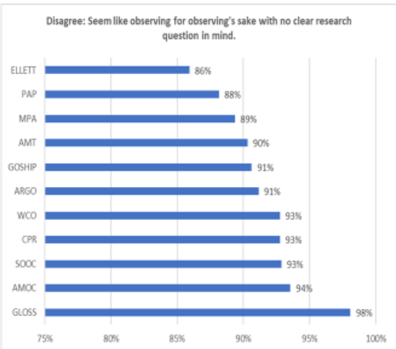
- The work on Marine Protected Areas (MPAs) was seen as aligned with the aims of regulatory monitoring and the work has co-design and co-funding from regulators.
- The Global Sea Level Observing System (GLOSS) tide gauge network was seen as something that should be more of an operational service. Within the UK, these gauges are funded by Defra through the Environment Agency for operational storm surge flood warning. The gauges under consideration are located South Atlantic oceanic islands and in Antarctica where there is limed operational use and the primary purpose is scientific at locations representative of the open ocean.

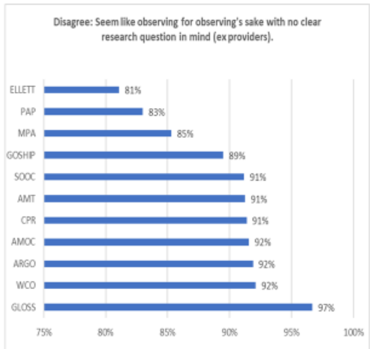
18. Consistent with the general response at the beginning of the survey, respondents disagree – a minimum of 86% (81%) - with the proposition that sustained ocean observing programmes could be deemed as “observing for observing’s sake”.

19. Free text opinions expressed on the motivation for specific observing systems are at Appendix 4.

Disagree that these are ‘observing for observing’s sake’

All respondents **Excluding providers**





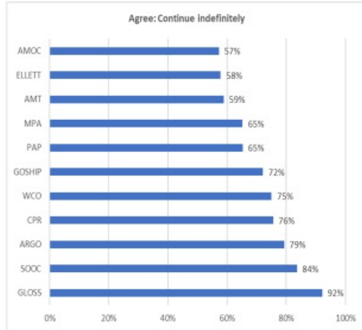
20. There were nuances around these opinions for certain observing systems, as shown by the responses when in ranked order of strength of response. The differences are mostly small.

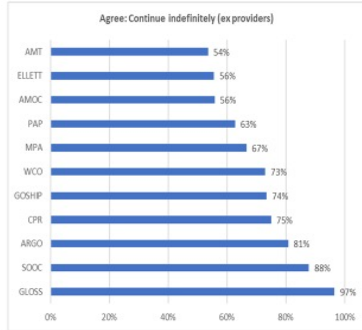
SUPPORT FOR CONTINUATION OF THE OBSERVATIONS

21. Whilst the opinion of most was that they wanted to see the existing observations continue, there was recognition that, for some observations, there may come a time when they should transition into some other form, including an operational service or statutory monitoring. Equally, it was clear that most respondents did not think now was the time.

These observations should continue indefinitely

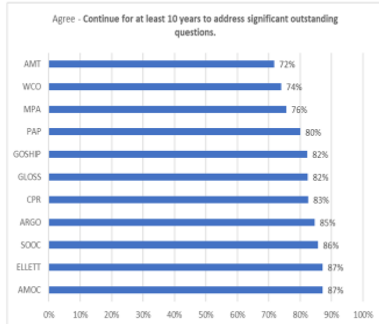
All respondents **Excluding providers**

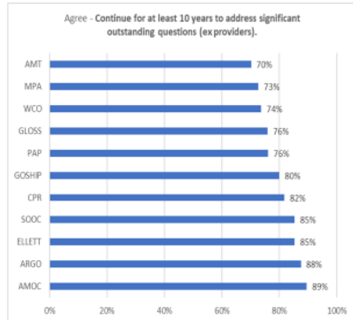




These observations should continue for next 10 years

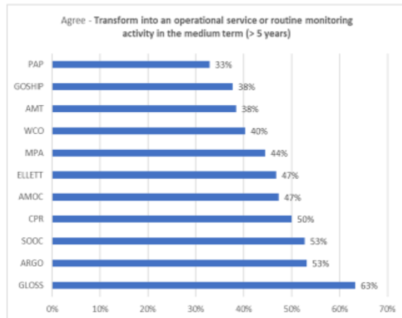
All respondents **Excluding providers**

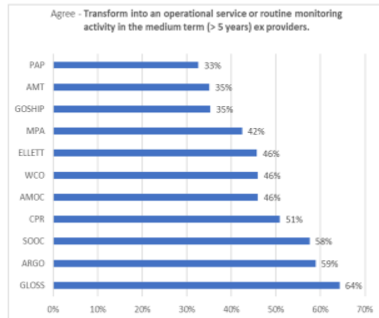




These should transform into routine operational monitoring but later than next 5 years

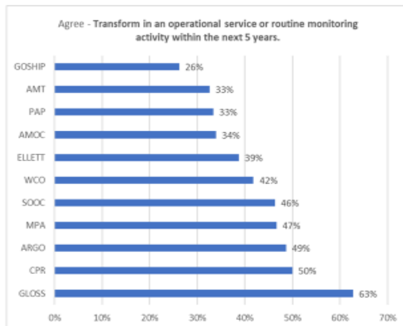
All respondents **Excluding providers**

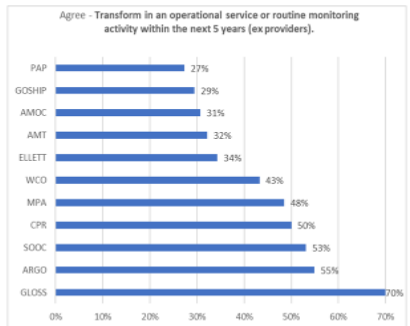




These should transform into routine operational monitoring in next 5 years

All respondents **Excluding providers**





These should transform into statutory monitoring in next 5 years

All respondents **Excluding providers**

22. The willingness of other organisations to transform observations into routine operational or statutory monitoring is untested for these cases (e.g., Government, Devolved Environment departments, Met Office). Co-design of observations would ensure delivery of monitoring to the relevant environmental, natural resource or hazard indicators for which the related non-R&D motivated agencies are responsible.

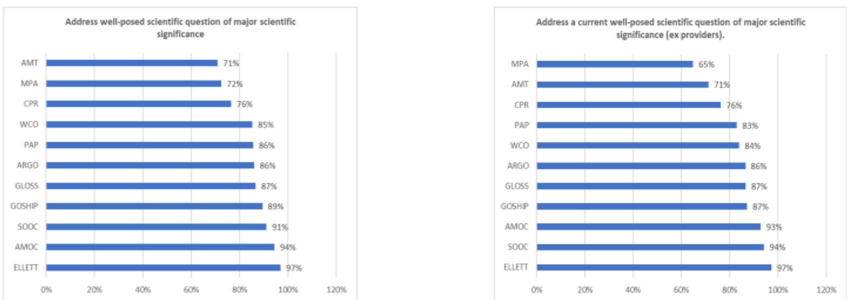
23. The appetite of other agencies to take on new (discretionary) observing commitments is not high, especially where that could displace core commitments – e.g., atmospheric observing for Met services and statutory obligations (Government Departments and agencies). Observations tend to be regarded as discretionary by statutory agencies where is a high need or interest in making those observations (a reason why even Argo primarily remains funded by R&D rather than 'operational service' budgets in most nations across the world).

SCIENCE QUESTIONS ENABLED

24. There is some discrimination between observing systems regarding opinions on the specificity or otherwise of the science question they address.

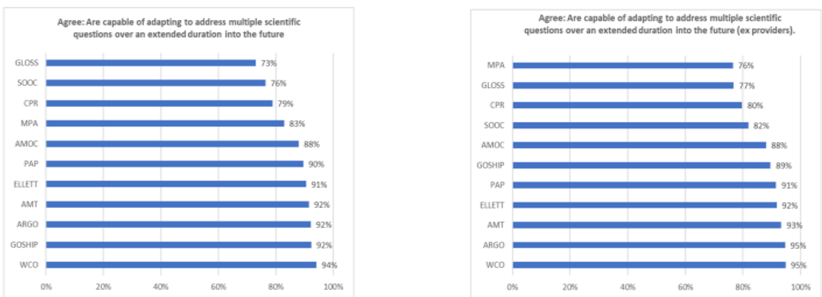
Well posed scientific question of major scientific significance

All respondents **Excluding providers**



Capable of addressing multiple scientific questions

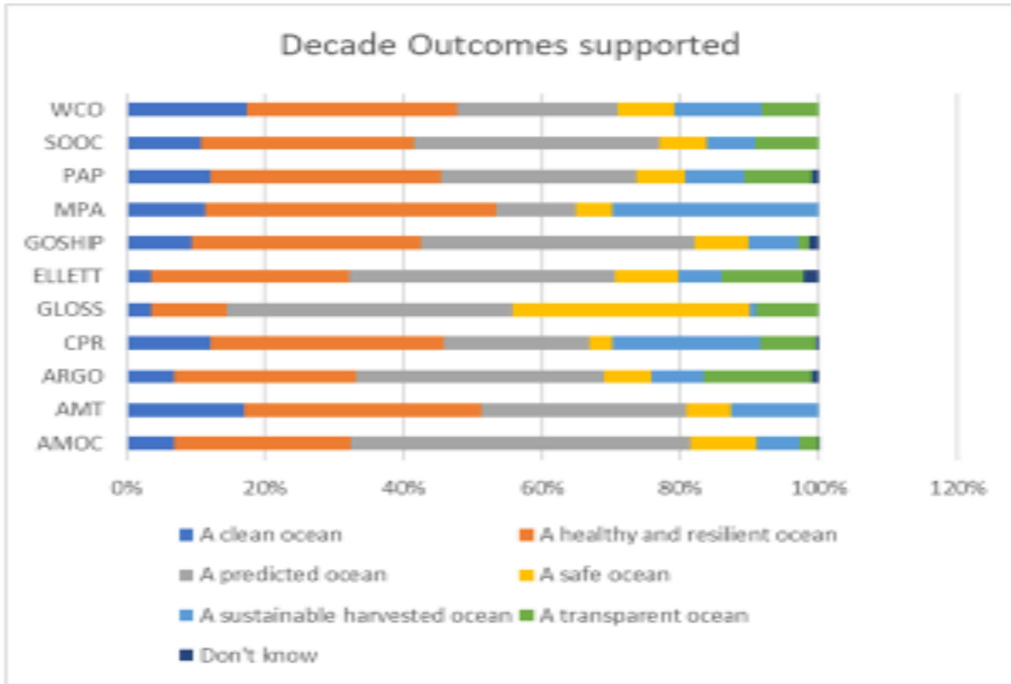
All respondents **Excluding providers**



25. For example, in the opinion of respondents, the Western Channel Observatory (WCO) can address multiple scientific questions but scores lower as to whether it is addressing a well posed scientific question. The Atlantic Meridional Circulation mooring array (AMOC) has almost the inverse profile. The difference in nature between observing systems was remarked upon independently by the Panel (see later below).

SOCIETAL OUTCOMES OF THE OBSERVATIONS

26. The United Nations Decade of Ocean Science has identified areas of societal beneficial outcome sought from its outcome-oriented vision of 'the science we need for the ocean we want'. The outcomes most prominently supported by the observations in the opinion of respondents were (a) 'healthy and resilient ocean' which refers to the health of marine ecosystems and the role of the ocean as a heat and carbon sink mitigating climate change and (b) a predicted ocean which recognises the role of sustained ocean observations in supporting climate and biodiversity assessments and projections and for informing coupled earth-system predictive models used to test future scenarios and make regional-scale predictions. Opinion on the GLOSS programme stands out as an exception as being viewed as supporting the 'safe ocean' outcome, reflecting the importance of global- and regional- mean sea level measurements in relation prediction of future inundation and the changing frequency of extreme sea level events.



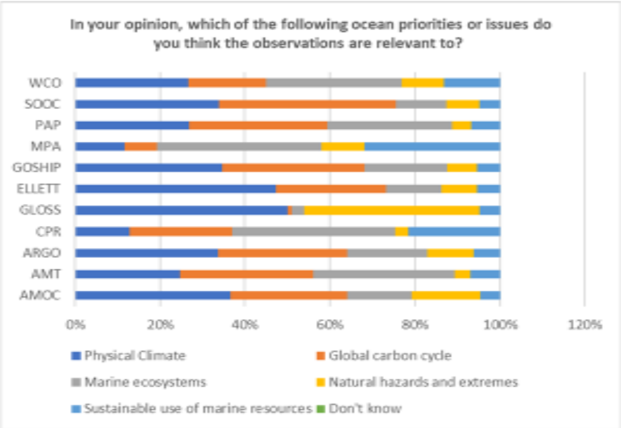
Ocean Decade outcomes supported by these observations. (All respondents)

SCIENTIFIC AREAS ENABLED BY THE OBSERVATIONS

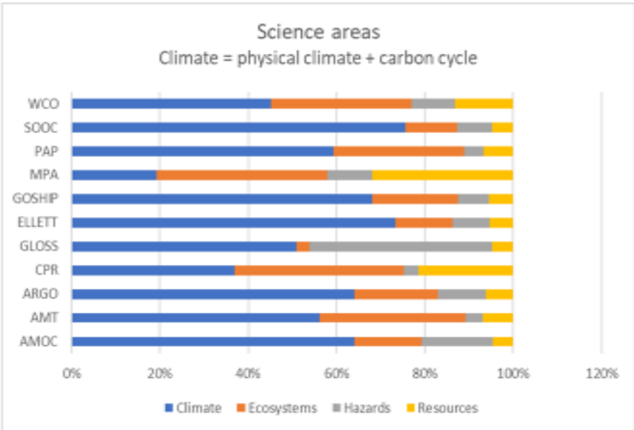
27. The sustained observations under consideration were viewed as supporting a diverse range of scientific interests. The Global Ocean Observing System 2030 strategy identifies the priority to expand beyond Essential Ocean Variables (EOV), relating to the physical climate system and into more biogeochemical and ecological parameters.

28. Respondents considered that these UKRI-funded observing systems have already expanded beyond the physical climate variables and include, for example, ocean carbon. Taking physical climate and carbon cycle measurements together as 'climate', these sustained observing systems contribute substantially to climate science. Typically, about

80% concern climate and marine ecosystems. As climate change and variability act at basin-decadal scales in the ocean, respondents supported the continuation of sustained observations, linked to coordinated global efforts. Again, the Marine Protected Area is an exception, being tightly linked to marine ecosystems and resources. GLOSS observations are mostly relevant to climate and hazards.



Science areas supported by these observations. (All respondents)



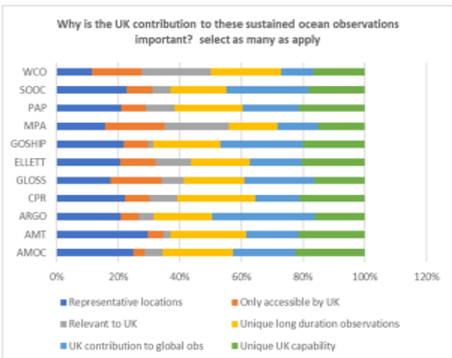
Science areas enabled. (All respondents)

VIEWS ON WHY THE UK SHOULD MAKE THESE PARTICULAR OBSERVATIONS

29. Respondents were asked why the UK should make these observations. There was no stand-out answer and respondents selected, fairly evenly, from across the options.

Why UK contribution of this observing is important

All respondents



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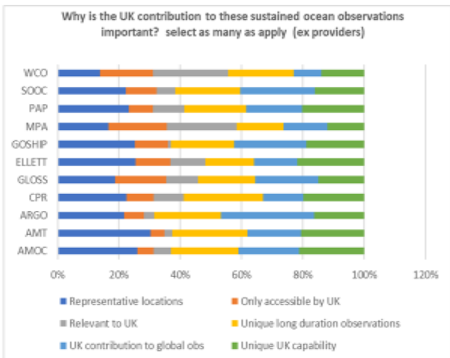


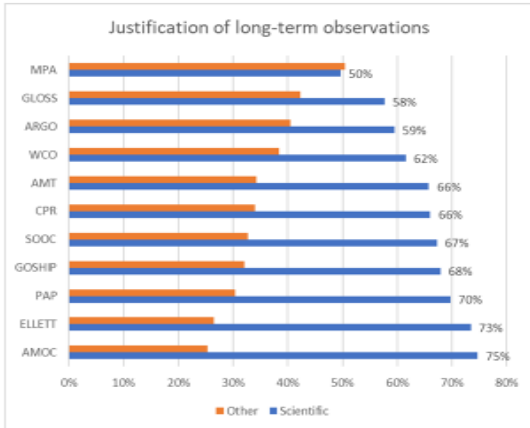
SPATIAL SCALE OF OBSERVATIONS

30. Respondents considered that the observations predominantly had spatial-scale coverage at global or ocean basin-scale, with the Western Channel Observatory (WCO) and Marine Protected Area Survey (MPA) being localised. Although the PAP deep-sea observatory is in deep international waters, it was recognised that it also has a North Atlantic basin-scale dimension.

TEMPORAL SCALE – LONG TERM OBSERVATIONS

31. Respondents were asked about justification for long temporal scale (sustained) observations. Three propositions had a strong scientific basis: (a) inherently long timescale of the process under investigation; (b) low signal to noise ratio requiring long-duration measurements to detect; (c) intermittency of the processes under investigation, needing long duration measurements to detect. Other options included speculative detection of signals; providing an operational service; the need to feed regular marine management or other ocean assessments.

All respondents



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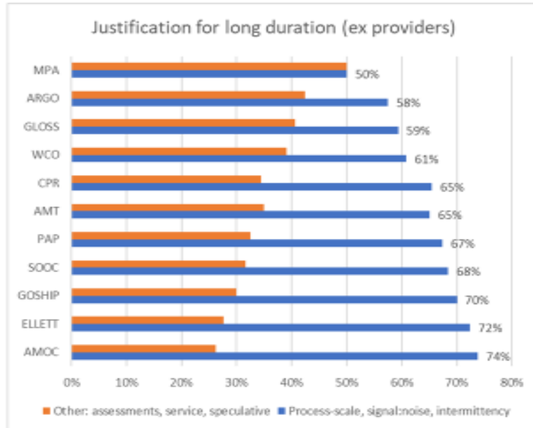
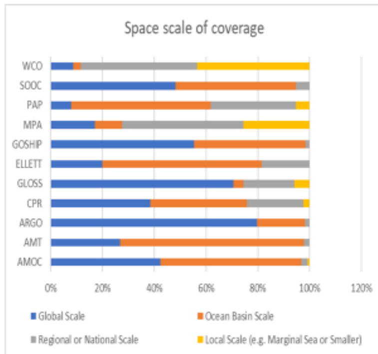


Spatial coverage

All respondents



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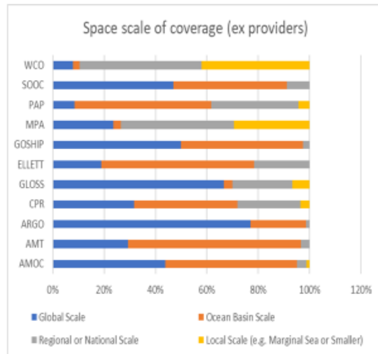


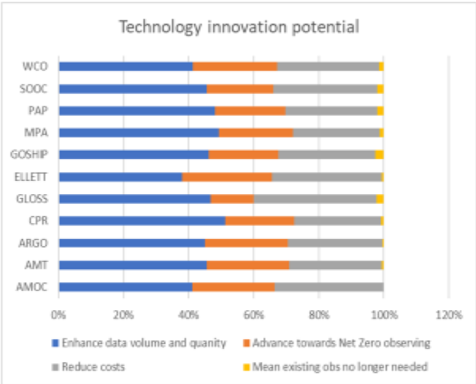
32. Free text comments on the rationale for sustained ocean observations amplify the above and are at Appendix 4.

VIEWS ON OPPORTUNITIES FROM NEW TECHNOLOGIES

33. Respondents were asked about new technologies e.g., new sensors and autonomous mobile observing platforms like sea-gliders and autonomous underwater and (small) un-crewed surface vehicles (AUV, USV). The main opportunity

(about half of responses for each system) was the ability to collect more or higher quality data; the next concerned cost reductions (more higher quality data at less cost). Respondents were clear that new technologies would not mean the observations being made by the systems under consideration would no longer be needed. Free text opinions on new observing systems and innovations are at Appendix 4 and summarised later.

All respondents



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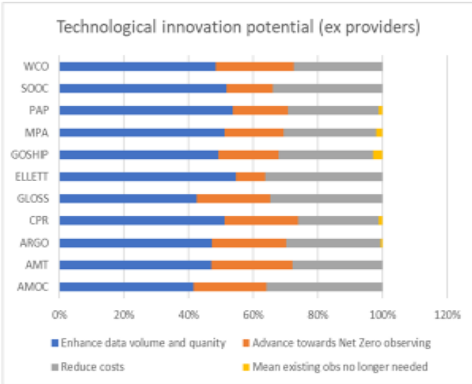


ONLINE WORKSHOP WITH MARINE SCIENCE COMMUNITY

34. Preliminary findings of the survey were presented to the NOC Association of Marine Science National Capability Beneficiaries (NOCA) AGM on 23 June 2022.

35. Breakout discussions focused on:

    - What questions will require sustained observations over decades, and, for those questions, what types of Sustained Observations (SO) are required?
    - What will UK sustained observing look like from 2030 and beyond?
    - What innovations might change current methodologies and enable new SOs?

36. The group commented that the ocean takes up over 90% of excess global warming heat and is the largest above-ground reservoir of carbon on the planet (>35,000 Giga tonnes) and whilst having a biomass <10% of terrestrial biomass, it turns over with much higher productivity rates (e.g., marine plants produce about the same amount of oxygen as all terrestrial). The group identified that the high-level science question to be addressed which specifically needs sustained ocean observations to tackle it given the space and time scales involved - is: **How does the ocean system work and how will it work in future under human-perturbed conditions?**

37. There is a need to identify the causes of change against a background of significant natural variability and then design policies and solutions to mitigate and adapt to human-caused perturbations of the marine system. Actions concern climate mitigation and adaption and reversing the cycle of decline in the health of the ocean ecosystem which has resulted from climate change and other cumulative human stressors – where problems and solutions are interlinked ('ocean-climate-biodiversity nexus).

38. Specific dimensions of the high-level question concern:

    - **Climate:** uptake and redistribution of heat in the ocean and ocean/atmosphere interactions, and sea level rise;
    - **Ocean-climate-biodiversity nexus:** how ocean physics e.g., warming, mixing, circulation interacts with ocean chemical and biological change and variability;
    - **States and rates:** quantifying ocean budgets (e.g., inventories or carbon, organic nutrients, oxygen)

and flux rates, constraining and reconciling with models to indicate the role of the ocean in major global biogeochemical cycles;

    - **Quantifying natural variability, extremes, marine carbon cycle, species and ecosystems response to changes;** signal to noise and signal to variability ratios and attribution of change and variability; impacts on biodiversity and microbial ecosystems;
    - **Change in poorly observed parts of the ocean:** e.g., larger biology, particularly deep sea and change in rapidly changing parts of the Earth system.

39. Sustained ocean observations need to be developed in the following areas:

    Expand range of variables

    - Expand the range of variables measured – extending from physical to biogeochemical and ecological variables (this priority is identified in the GOOS 2030 Strategy).

    Enhance system integration

    - Increase integration across observing systems including those funded by UKRI-NERC. Integration includes integrating data providing complementary information on aspects of the marine system (e.g., carbon cycle). The latter is an issue at global scale.

    Pull through science to policy

    - Ensure maximum pull-through of data and information from observing systems to support science and provide evidence to underpin policy.

    Ensure findable, accessible data

    - Ensure data are managed for the long-term and are openly availably/findable/accessible (FAIR principles). Visibility of sustained observing systems and their data could be enhanced.

    Innovation: develop technology and skills

    - Identify opportunities for innovation and use of data from new technologies e.g., autonomous platforms, genomics, eDNA incorporated into sensors; benthic crawlers and animal borne sensors (engaging with larger organisms); low cost open-source technologies, enhanced satellite communication coverage over the ocean, Artificial Intelligence, accessible repositories and fit for purpose data repositories. Innovation should be considered in the context of the combined Observation/Data/Prediction infrastructure to maximise information value for the investment. It will be important to identify the skills needed both to develop technology and use new knowledge.

40. Most large-scale questions of ocean change and variability depend upon knowledge of change and variability of the physical system, but it is important to link physical, biogeochemical, ecological and human processes to support policy actions.

41. In developing ocean observations into the future, the following important issues were identified:

    - The framework of high-level science plans (international and national) ensures that data requirements and sustained observations planning link to marine science priorities;
    - Models identify the data analysis and products needed to address policy questions (i.e., user-requirements in system design that line up with the GOOS 2020 Strategy);
    - Coordination with Government agencies.

- Improved digital representation with data infrastructures, Quality Assurance, archiving and data distribution, discoverability and accessibility.
- Public engagement to share knowledge about the ocean and its benefits.

EXPERT PANEL REVIEW

42. The Panel of UK and international members met on 4 July 2022 to consider the need and effectiveness of the sustained observations. Members prepared comments and scores against descriptors of scientific need and effectiveness.

43. The Panel commented that 'the UK is to be commended for undertaking this exercise and sharing its findings with a wide international audience would be very beneficial'. The Panel made generic comments applicable to all the systems reviewed, namely:

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

44. The Panel provided moderated comments on each observing system and an overall moderated consensus score for each system on a five point scale, based on the assertions below as a guide.

    Science need for the sustained observation

    - Primary motivation is advancement of scientific knowledge and understanding.
    - Is well posed, tractable science question or challenge to be solved.
    - The science challenge is of international significance. Consider either individual UK observations or the whole network contributed to.
    - There are clear scientific reasons why this observing be commenced or continued now.
    - Data will be used by a wider science community beyond group making observations.
    - It is important for the UK to support this particular observing element.

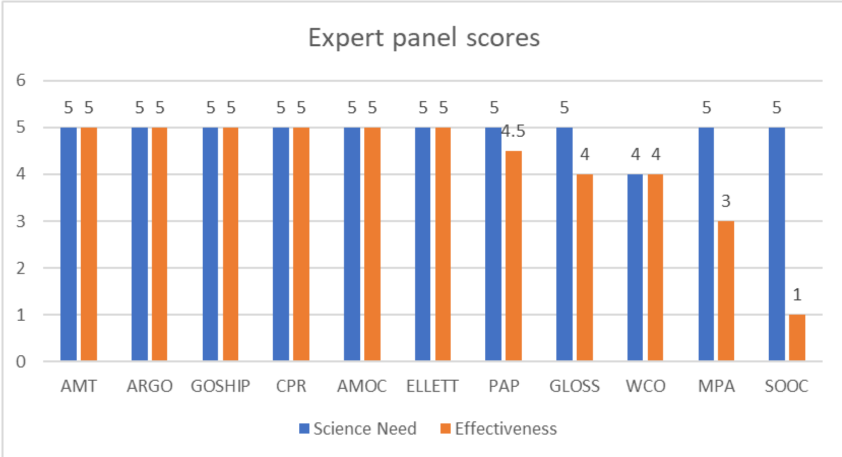
    Effectiveness of the sustained observation in meeting needs

    - There are wider direct and/or indirect societal and other added value science and innovation benefits of this observation.
    - Systematic, sustained observation is the essential methodology to meet the science need.
    - [Measurements are long duration but] the space-scales of processes are addressed adequately in this observing strategy (e.g., observations alone or as part of a network).
    - Up to 2030, is potential for technological innovation in how observations are made.
    - If necessary, this UK contribution could be scaled back in scope, coverage, or sampling frequency to an irreducible core and still achieve internationally important science needs.
    - The uniqueness/distinctiveness of UK contribution is important in a global context of sustained ocean observations, for example: (a) uniquely important location, (b) demonstrating new approach that could be transformative (c) few countries able to do this.

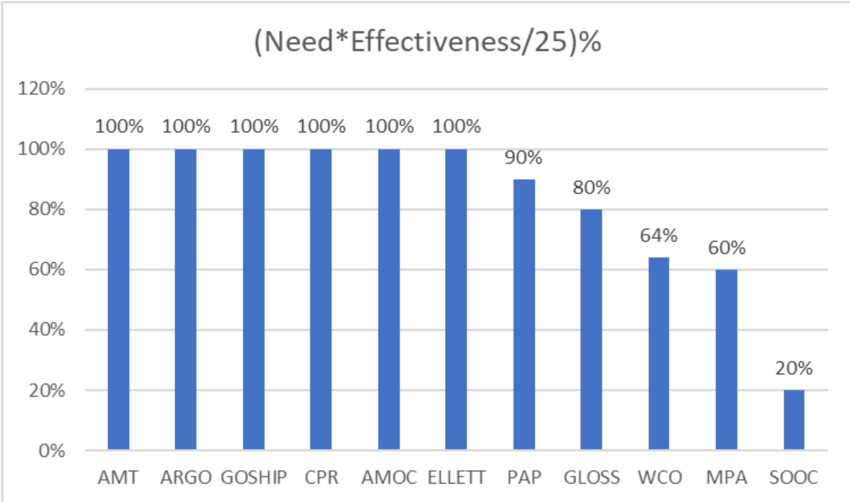
45. The overall view of the Panel was that all of the observing systems reviewed were contributing to advancement of science. This is reflected in the moderated scores which were similar to the outcome of the online survey which discriminated between systems in a nuanced way. There was no scientific basis to completely discontinue any.

46. Scores were uniformly high on science need and consistent with their comment that the scientific need for all was high and with the findings of the online survey. Some discrimination was possible based on the effectiveness of the observations in meeting the need.

47. In some cases, low effectiveness score indicated that more investment was needed (e.g., SOO-C, MPA) where in others that there was a need for more focussed prioritisation (e.g., WCO, PAP).



48. The scores on both axes were combined into a single score arrived at as the product of need and effectiveness scores.



COMPARISONS OF VIEWS

49. The results from the survey and Panel were collated.

(a) The scores for the survey are the averages of the percentage of respondents agreeing or strongly agreeing with each of the three statements most directly relevance to the science namely:

- addresses a well posed scientific question of major significance;
- having a demonstrable impact in advancing knowledge and understanding;
- capable of adapting to address multiple scientific questions over an extended duration into the future.

(b) The scores for the Panel were the product of the scores for scientific need and effectiveness in meeting ned converted to a percentage.

OBSERVATION	SURVEY %	PANEL %	AVERAGE OF SURVEY PLUS PANEL %
ELLETT	93	100	97
AMOC	93	100	97
GO-SHIP	92	100	96
ARGO	92	100	96
WCO	91	64	78
PAP	90	90	90
SOOC	86	20	53
GLOSS	85	80	83
AMT	85	100	93
CPR	82	100	91
MPA	77	60	69

50. The rankings of individual observing systems do vary so there is not complete consistency of view and a widespread in some cases. Moreover, some of this reflects the fact that scores are generally high and, as described before, the analysis is looking at nuances within an overall message that all are seen as scientifically very important. However, within this caveat, two stand out for consistency:

- AMOC was consistently in the top four;
- MPA was consistently in the bottom four but largely because of the interpretation of 'effectiveness'.

51. A ranking was developed based on an analysis of rankings (which shows the spread of these).

SURVEY	RANK	PANEL	RANK	FREQUENCY OF RANKING												TOTAL
				RANKED	1	2	3	4	5	6	7	8	9	10	11	
ELLETT	1	AMOC	1	AMOC	2											2
AMOC	1	AMT	1	ELLETT	2											2
GO-SHIP	3	ARGO	1	CPR	1									1		2
ARGO	3	CPR	1	ARGO	1		1									2
WCO	5	ELLETT	1	GO-SHIP	1		1									2
PAP	6	GO-SHIP	1	AMT	1							1				2
SOOC	7	PAP	7	GLOSS								2				2
GLOSS	8	GLOSS	8	WCO					1				1			2
AMT	8	WCO	9	PAP						1	1					2
CPR	10	MPA	10	MPA										1	1	2
MPA	11	SOOC	11	SOOC							1				1	2

SUMMARY OF COMMENTS MADE BY THE PANEL

OVERALL:

- The UK is to be commended for undertaking this exercise and sharing its findings with a wide international audience would be very beneficial.
- All of the observing systems are of immense scientific value and should be continued.

FOR ALL OBSERVING SYSTEMS:

- The Panel commented that comparison across the different sustained observations is not possible due to their specialist nature, hence there was a concern about 'an apples-and-pears-comparison'.
- The societal benefit, specific purpose and science questions addressed should be articulated more clearly and more visibly (and preferably collated in one place) for non-specialist audiences.
- For several observing systems, data should be readily accessible in a timely way and comply with FAIR (findable, accessible, interoperable, reusable) principles.
- There should be a more integrated and cross 'systems view' across all observing systems e.g., different systems contribute in different ways to building a picture and reducing uncertainties in the state of inventories and fluxes of carbon (this is an observation both about the UK contributions and the international systems as a whole).
- Common success metrics should be developed for benefits from the observing systems e.g., for uptake of available data, training, capacity development and innovation.
- Opportunities for transformation in these observations through technological and other innovations should be identified and plans/roadmaps to achieve these developed.

ATLANTIC MERIDIONAL TRANSECT

- Provides one of the few opportunities to measure biomes across North and South Atlantic via a research ship of opportunity programme.
- Its role as a platform for training, science and innovation is at least as important as being a sustained ocean observing programme.
- Should consider expanding the footprint of these observations with autonomous platforms deployed and recovered during out and return legs.
- The programme could link with other similar transit legs by other nations.
- As a ship of opportunity programme, it operates at an irreducible level.

ONE ARGO PROFILING FLOAT PROGRAMME

- The standard Argo programme has transformed knowledge of ocean heat uptake and reduced uncertainties. It is an exemplar of international cooperation in globally distributed ocean sensing. The value of data comes from the collective basin- and global- scale contributions of multiple nations including the UK in collaboration with the Met Office.
- Deep Argo and Biogeochemical Argo will need to be funded for some time not least because operation of unattended biogeochemical and deep sensors and data interpretation is firmly a research endeavour at this stage. There are almost no examples to date worldwide of standard Argo transitioning to an operational phase.
- The present UK contribution to the global programme is probably at minimal levels (and the UK is a major data beneficiary) so scaling back is not recommended.
- Gliders are ideal for bridging the gap where Argo data becomes less easy to obtain when approaching the shallowing continental margins and, except the Ellett Array (see below), the UK has, as yet no planned sustained observing glider programme and consideration should be given to this possibility. Animal borne sensors have been pioneered by the UK and are good where Argo fades out in marginal ice zones (MIZ); there is no sustained UK programme for animal borne sensors in these regions.

GLOBAL SEA LEVEL OBSERVING SYSTEM (GLOSS)

- GLOSS is a well organised programme internationally and coastal and island gauges complement measurements from satellite altimeters in establishing the global and regional footprints of sea level rise; oceanic island measurements are critical.
- UKRI contribution is focussed on a small number of South Atlantic oceanic islands where the UK has unique access and the programme is irreducible in scope. May be opportunities to co-locate other sensors to take advantage of infrastructure at these sites e.g., telemetry.
- Consider expanding the UK programme to support observations and capacity development in areas where there are major caps in coastal sea level data (notably Africa).
- There is concern about the inadequacy of data quality for climate trends and other purposes from the UK's network of designated seven GLOSS gauges, within the UK's mainland network of 42 flood gauges operated by the Environment Agency. The case for rectifying this is a priority, given the UK's leadership in sea level science and in promoting global engagement in the GLOSS programme.

GLOBAL OCEAN SHIP-BASED HYDROGRAPHIC INVESTIGATIONS PROGRAMME (GO-SHIP)

- At the moment, this programme is the only way to achieve high accuracy, systematic measurement of physical and biogeochemical (including carbon) state variables, covering the global ocean, at least once a decade. It is vital for defining the ocean carbon inventory. It will be essential until autonomous technologies and associated, unattended sensor capabilities are more mature and will need parallel running for a considerable duration for cross calibration. In particular, it is 'super important' for calibration of unattended sensors from Biogeochemical Argo, Deep Argo, standard Argo, where accuracy and stability will remain a formidable challenge for the foreseeable future.
- GO-SHIP needs highly capable ocean and global class ships which the UK is well placed to contribute. The value of data is from the global array of transects rather than individual sections alone. It is questioned whether the UK is contributing to GO-SHIP at a sufficient level (four lines) given its capabilities and there appears to have been some reduced UK engagement in the programme at the international level.
- A priority is to expand the range of biological variables sampled on GO-SHIP lines.
- GO-SHIP lines offer important training and capacity development opportunities as a science platform, and it will be important that GO-SHIP transects are used to deploy standard, Biogeochemical and Deep Argo floats.

SHIP OF OPPORTUNITY OCEAN PROGRAMME - CARBON MEASUREMENTS (SOOP-CARBON)

- Surface carbon measurements complement GO-SHIP subsurface inventories by focussing on the surface fluxes of carbon which is critical to reduce uncertainties to within reasonable bounds (<10%). There are major uncertainties for which expanded ocean surface carbon uptake measurements are critical to address – just one set of uncrewed surface vehicle (USV) measurements has raised questions as to whether the Southern Ocean is becoming an atmospheric carbon source rather than sink. There are major discrepancies (50%) between observational and model estimates of surface ocean carbon fluxes.
- The UK contribution to this ship of opportunity programme seems to have ended (UK Caribbean container ship lines) and this is symptomatic of a wider issue as container ships are being switched between routes rather than plying consistent routes. One solution is to 'globalise' carbon measurements so that most ships have the equipment so it is less problematic if they switch routes.
- There is a major opportunity ('ripe for transformation') to switch carbon measurements to USVs like wave gliders, saildrones and gliders for which investment and trialling will be needed. The UK science community will need to take a view as to whether it wants to be in the forefront of leading this transformation which it is well placed to do.
- At a minimum, all UK research ships (including those operated by UKRI) should be enabled to routinely collect surface pCO_2, regardless of whether needed for the specific expedition.

GLOBAL CONTINUOUS PLANKTON RECORDER SURVEYS (CPR)

- These provide unique records of a biological Essential Ocean Variable (surface plankton) expansion which is a priority for GOOS. The strength of the CPR is the coverage it gives multi-decadal at basin-scale as part of the Global Alliance of Continuous Plankton Recorder Surveys (GACS). Some UK records in the North Atlantic are the longest in the world (80 years +). Obtained by ships of opportunity towing CPRs trans-Atlantic, they provide most of what we know of basin-scale changes in North Atlantic plankton distributions at species level in response to climate change, including regime shifts and contribute to global- and regional-scale state of the ocean assessments (e.g., Oslo and Paris Conventions (OSPAR)).
- The UK contribution to CPR is unique and the records are of global significance.
- There is no other way of making equivalent measurements at present which, uniquely, retain the biological samples (captured on silk) and enable reanalysis to address new issues.

- Adding sensors onto CPRs is easy and will enhance the range of variables measured.
- A strength of the CPR is continuity and consistency of use of a simple technology over decades. Newer technologies should be developed to obtain information about surface plankton, although it is doubtful they will be able to provide the capability equivalent of the CPRs and so parallel running of CPRs and new techniques would be needed for a long time.

MARINE PROTECTED AREA REPEAT SURVEY (MPA)

- This programme involves repeat mapping and sampling of declared areas placed under marine protection, two of which are in deep (>1000m) water off the continental shelf and aim to track recovery from disturbance and impacts of climate change. The observations in deep sea protected areas are internationally significant and important for the UK to pursue, as presently, these are not being done elsewhere and the UK can offer unique capabilities.
- The science and techniques being developed by this programme for observing in deep sea protected and disturbed areas have important policy implications. Increasingly, the science and methodologies will be needed if deep sea mining proceeds and to support the new international legally binding agreement on conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction (BBNJ) currently under negotiation at the UN, which will provide the future legal basis for establishing MPAs in the high seas.
- Suitable spatial coverage is important within, and outside protected and disturbed areas and work is needed to establish the appropriate sampling intervals (presently envisaged as once in five years per site) and this may need to increase in the early phase at least.
- This is an area where co-resourcing by science and regulator funding is appropriate and where engagement of all key stakeholders is important, including those in Scotland. The science input is vital for developing techniques, introducing new technologies e.g., surveying with autonomous technologies and for investigation of climate change effects.
- This is an area that is ripe for innovation including use of novel sensors and use of environmental DNA (e-DNA), in addition to other new technologies, such as autonomous underwater vehicles for survey and imaging being used for these observations.

ATLANTIC MERIDIONAL OVERTURNING CIRCULATION ARRAY (AMOC)

- This programme has been a 'game-changer' in rigorously measuring the key components of the Atlantic part of the global conveyor belt thermohaline circulation, and initially, was thought impossible to measure. Reproduction of the overturning circulation is a critical test of performance of coupled Climate/Earth System models. Collapse or slow-down of the Atlantic Meridional Overturning Circulation (AMOC) is one of the critical tipping points identified in Intergovernmental Panel on Climate Change reports. This is the UK's most well-known ocean observation programme and was considered the number one priority to continue.
- The AMOC programme is to be commended for the way the array has been rigorously optimised, using model sensitivity analyses, enabling the number of moorings and cost to be reduced. Experimentation with gliders on Eastern boundaries continues to innovate and continued additional investment is needed to secure more real-time data return.
- Extension of measurements of the Atlantic overturning circulation into the subpolar North Atlantic (where sinking and overturning takes place) is important (see Ellett Array below) and other countries (e.g., USA, Canada, France, Germany) should share the responsibility. The UK should continue to lead the 26ºN observations with the US to preserve quality, given the extensive experience.

WESTERN CHANNEL OBSERVATORY (WCO)

- The WCO is one of only four presently operating sites on the European shelf - Helgoland (Germany), Stonehaven and Loch Ewe (Scotland) - where there are long biological records. Like all coastal observing systems, there are questions about representativeness of the site and effects of local processes. It consists of two sites in deeper and shallower coastal waters which gives some local spatial scaling. It covers an impressive range of observations, both benthic and pelagic, essential for benthic- pelagic coupling.
- The results are used in UK marine assessments because it is one of several long reference series for some species and it supports seasonal biological modelling. Whilst the ocean pH variable at WCO contributes to the Global Ocean Acidification Observing Network (GOA-ON), there could be better connectivity with other coastal monitoring sites in the UK, European waters and worldwide such as through the European Network of Marine Stations (Marsnetwork) and the World Association of Marine Stations (WAMS).
- The site is a platform for technological innovation, training and shorter-term process studies, in addition to the sustained observing component. It supports development and testing of the European Regional Seas Ecosystem Model (ERSM) and has supported building a satellite oceanography capability in ocean colour relating to ocean biology.
- Visibility and accessibility of the data could be improved, and the majority of authors and co-authors of publications are from Plymouth. There was a spread of views on this ranging from, "*this is natural because local expertise is helpful in interpreting this complex data set*" to, "*a real sustained observatory should produce data that is accessible and usable independent of the investigators that generate the data*". It is important to distinguish between an observatory contributing systematic observations globally (in the context of GOOS, say) and a long-term site for local science.
- The strength of the WCO is the comprehensive range of variables measured. A weekly sampling interval is deemed the appropriate interval. The intensity and complexity of sampling will have cost implications. Costs of observations was beyond the remit of the Panel; a cost-benefit analysis is recommended in relation to the other observations under consideration.
- The site is ripe for innovation in terms of use of autonomous vehicles, new sensors and use of e-DNA, for example and is demonstrating its use as a site for innovation.

PORCUPINE ABYSSAL PLAIN OBSERVATORY (PAP)

- This deep-sea observatory on an abyssal plain is one of only three deep sea biological observatories (one in Pacific and another in the Western North Atlantic). The PAP site is part of the OceanSITES network as part of GOOS. Expanding biological measurements is a priority of GOOS and ideally there would be 20 or so such sites worldwide. The PAP observatory is principally a UK activity and, as there are so few of these, the three oceanic sites referred to including PAP are of global significance (depth, longevity, biological EOVs).
- The PAP's relevant scale is the vertical (4,800m water column depth) and it measures carbon fluxes for sea surface to sea floor. It is the site from which much of present understanding derives concerning the multi-decadal coupling between surface processes and the deep-sea floor, including through episodic deposition of 'marine snow'.
- The site provides mostly a one-dimensional perspective (single mooring) but, given its location away from major boundary currents, this may be less of a problem than it would be in other locations. Nevertheless, it is important to periodically undertake broader area sampling to establish the wider spatial variation, possibly by undertaking more intensive activity in some years. If the number of physical oceanographic measurements could be increased at this site, this would help constrain the spatial variation.
- There is an opportunity to review the frequency at which the site needs to be visited.

- There is evidence of interesting innovation at this site, such as the development of sediment traps, real-time return of some data and use of autonomous underwater vehicles (AUV) for benthic survey and imaging. The site provides a platform for innovation and testing in a deep-sea context, for training and undertaking shorter term process-based science.

ELLETT ARRAY

- The Ellett Array consists of repeat glider transects and five moorings. The location captures a major part of the North Atlantic current inflow and the two-way connection across the Iceland-Scotland ridges, between the subpolar Northeast Atlantic and sub-polar Nordic Seas. Most recently it has been incorporated as the UK contribution on the eastern boundary to the full trans-Atlantic multi-national 'Overturning in the Subpolar North Atlantic Programme (OSNAP) array. The aim is to capture the overturning circulation across the basins where water sinking and deep-water formation occurs, extending the AMOC measurements made at 26ºN.
- The Ellett Array provides important information for the UK and Scotland (which has devolved responsibility for about half of the UK's marine area). In particular information about the connectivity between, and gradient across, the subpolar and subtropical ocean basins, will be needed to inform policy and marine management (e.g., regional climate, fisheries).
- The Ellett Array is highly commended for significant innovation that has taken place and is a pioneering example of where data gathering has been entirely moved to gliders from previous annual ship-based hydrographic sections undertaken since the 1970's. In doing so, full depth coverage has been partly compromised and the next innovation is introduction of deep gliders. The Ellett Array demonstrates how to migrate regular hydrographic sections off research ships.
- A key question is the degree to which the long-term future of the Ellett Array is coupled to OSNAP. It will be important to optimise the OSNAP array based on a long run of data and model sensitivity analysis (it took eight years for AMOC 26ºN). The criticality or otherwise of the Ellett Array within OSNAP would become clearer at that point. There is an independent case to continue the Ellett Array regardless of OSNAP because of the boundary inflows and outflows in the region and this case should be reviewed in the event that OSNAP were discontinued or significantly reconfigured.
- Pending review and optimisation of the multi-national OSNAP array, continuation of the Ellett Array is essential. The Ellett Array is as an early pilot of moving traditional ship-based observations to autonomous technologies and where innovations and learning is continuing (deep gliders). As the Biogeochemical (BGC) Argo Programme develops its coverage in this region, the Ellett Array is likely to have an important role in connecting the BGC Argo domain to the continental shelf which is one of the added strengths of glider transects.

PART FIVE: RECOMMENDATIONS AND CONCLUSIONS

RECOMMENDATIONS

1. Information about the ocean is essential for supporting global assessments for climate and biodiversity, including the IPCC 6th Annual Assessment Report (IPCC, 2021); IPCC Special Report on the Ocean & Cryosphere (IPCC, 2019); IPBES Global Ecosystem Assessment (IPBES, 2019); and the Second World Ocean Assessment (UN, 2021). The decade to 2030 will be critical in delivering knowledge about climate, biodiversity and the ocean.
2. There is a responsibility to future generations, to use our capabilities to undertake systematic observations to track the unprecedented, rapid ocean changes that are already underway, noting that the ocean is under-sampled in space and time and is continually changing.
3. The United Nations Convention on the Law of the Sea (UNCLOS, 1982) sets out the responsibilities of States Parties to undertake scientific research and observation in the ocean to increase knowledge and understanding of the marine environment and its resources.

SYSTEMATIC, SUSTAINED OCEAN OBSERVATIONS

4. Types of ocean data collection that are systematic and extended are critical to address the most significant scientific questions operating at regional- and basin-decadal scale (e.g., climate change, ecological regime shifts), especially where processes have:
    - inherently large space-time scales (scales which are linked in the ocean);
    - low signal to noise ratio, where long data series are needed to detect and attribute signals of concern;
    - intermittency or involve rapid state-changes.

INTERNATIONAL CONTEXT

5. There is international consensus on the priorities for knowledge and understanding to support the implementation plan (2021) of the UN Decade of Ocean Science for Sustainable Development 2021-2030 which needs:
    - solution-orientated and transformative ocean science ('the science we need for the ocean we want') in support of the Decade's knowledge challenges concerned with pollution, food security, ecosystem health, supporting a sustainable ocean economy, climate change;
    - to address key infrastructural challenges to 'ensure a sustainable ocean observing system across all ocean basins that delivers accessible, timely and actionable data and information to all users' (Decade infrastructural challenge seven).
6. The Global Ocean Observing System 2030 Strategy (IOC, 2019) calls for expansion and more sustainable funding for the

global ocean observing system:

- with priorities on climate change and ocean [ecosystem] health,
- consistent measurement to agreed standards of defined Essential Ocean Variables;
- expansion of sensing outwards from variables relating to the physical climate system (e.g., heat, sea level) to a greater range of biogeochemical and ecological variables with investment to increase the Technology Readiness Levels (TRL) of these.

7. There are few funding actors in the 60% of the ocean area beyond national jurisdictions i.e., outside Exclusive Economic Zones (other than meteorological services interested in upper ocean weather-related physical variables). Research investments are almost exclusively the source of support for ocean observations in this area (Part XIII, UNCLOS, Marine Scientific Research).

THE 'VALUE CHAIN' OF OCEAN INFORMATION, KNOWLEDGE AND UNDERSTANDING

8. Systematic sustained ocean observations are not undertaken in isolation and are the critical foundation (and the most costly and difficult to sustain) of an ocean knowledge and information value chain and that data generated from them:
    - are a public good;
    - can be used to create new knowledge to advance scientific understanding and to provide actionable information integral to design, testing and evaluation of ocean actions solutions ('you cannot manage what you cannot measure');
    - are important for initialising and constraining predictive coupled ocean earth system and coupled-climate models.
9. Systematic streams of ocean data for sustained ocean sensing systems will be central to future decision-making tools, such as Digital Twins of the Ocean and for initialising, constraining and assimilating into global and regional ocean simulation models for forecasting, prediction, scenario investigation and scientific hypothesis testing.
10. When synthesised at global and regional scale, data from systematic sustained ocean observations play a key role in providing the scientific evidence base to:
    - inform domestic and international public policy;
    - highlight potentially rapid changes unfolding in the non-linear ocean system (tipping points);
    - inform with scientific evidence design of well-considered and responsible ocean actions;
    - provide evidence for regular state of the ocean, climate and biodiversity assessments, and inform scientific-based monitoring and evaluation of the effectiveness of policy actions.
    - the ocean economy.

THE UK CONTEXT

11. The UK Government and Devolved Administration landscape is noted, especially:
    - the UK Research & Development Roadmap (2021); the UKRI Strategy (2022) and UKRI-NERC's implementation which support the government ambition for the UK to be a '*global science superpower*';
    - the UNESCO Global Ocean Science Reports (2017 & 2020) which show the UK to be a global ocean science superpower against some metrics.
12. In the context of being an ocean science superpower, the UK must remain a 'good global science citizen', leading and engaging in areas needing international scientific cooperation, including programmes of coordinated global- and basin-scale 'in- and under-water ocean sensing - where no one nation can make the observations alone and where meaningful results are only obtained by synthesising the big picture from individual national contributions (e.g. ocean heat and carbon uptake and content, sea level rise, marine ecological changes across ocean basins).
13. There are several UK institutional actors making and funding marine observations, both within and beyond the UK's own Exclusive Economic Zone and for different motivations (scientific research, marine environmental and resource management, operational weather forecasting and hazard warning). These should collaborate to share data and avoid duplication of effort.
14. The main systematic sustained observations outside the UK EEZ are funded by UKRI-NERC and made by the National Oceanography Centre (AMOC, PAP, Argo, GO-SHIP, GLOSS, SOO-C), Plymouth Marine Laboratory (AMT), Marine Biological Association (CPR). The Met Office contributes to ocean observations outside the UK through Argo, fixed weather buoys, drifting buoys and voluntary observing ships.
15. In the UK EEZ, extensive sustained observations and monitoring are made by public agencies (Cefas, Environment Agency, Met Office, Marine Scotland Science, Natural Resources Wales, Scottish Environment Protection Agency, Dept for Environment Northern Ireland. UKRI-NERC supports three programmes inside the or straddling the UK EEZ, namely Ellett Array (SAMS), Western Channel Observatory (PML and three MPAs (NOC).

RECOMMENDATIONS

16. Recommendations are intended to be resilient to funding increases or decreases; neither increase nor decrease has been presumed. Prioritisation of observations and understanding where they can be improved is needed to ensure maximal scientific and societal return.
17. Drawing on published materials, national and international strategies and views expressed by the marine science community, a NOCA workshop and a Panel of UK and international experts, the Chief Executive of the National Oceanography Centre offers to UKRI-NERC the following recommendations regarding future prioritisation of investment in systematic, sustained ocean observations.

GENERAL RECOMMENDATIONS (SCIENCE)

- **ONE** - The international-level challenge (e.g., Ocean Decade) to 'ensure a sustainable ocean observing system across all ocean basins' should be integrated into plans for future funding, as data needs to inform, with evidence, action at the ocean-climate-biodiversity nexus.
- **TWO** - Open, timely access to data should be a primary criterion for funding ocean observations that claim the need to be sustained; each should have a data management plan.
- **THREE** - There should be better explicit alignment between UKRI-NERC investment in sustained ocean observations priorities and investments to promote uptake of new observing technologies through the Net Zero Oceanographic Capability Programme e.g., see Recommendation 4.

OBSERVING SYSTEM SPECIFIC RECOMMENDATIONS

- **FOUR** - The ship of opportunity ocean surface carbon programme (SOO-C) should be discontinued as it is because it is ineffective due to ship-routing considerations. Instead, there needs to be a proposal for how these high priority measurements can be made effectively and on a sustainable basis e.g., using autonomous platforms such as un-crewed surface vehicles (USV).

- **FIVE** - The following sustained observing programmes should be continued as high priority on the basis of international strategy and as reinforced by consultation findings:

  a. The **One Argo** profiling float programme (collaborative with Met Office). UKRI-NERC funding should focus primarily on Biogeochemical- and Deep-Argo and the scientific and technical capabilities to ensure data quality from unattended ocean sensors which will be vital as a model for all future unattended sensing on autonomous platforms.

  b. The **Global Ocean Ship Based Hydrography Programme (GO-SHIP)** which goes hand in hand with any unattended ocean sensing (including Argo) by providing 'gold standard' high-accuracy full-ocean-depth, trans-basin coverage. With additional resources, consideration should be given as to whether the UK, as one of few countries with the relevant national capabilities, should increase its contribution of GO-SHIP lines.

  c. The **Continuous Plankton Recorder Survey (CPR)** which is one of the only and longest-running multi-decadal basin-wide ecological surveys in the world. Continuing integration of newer measurement technologies onto the4 existing recorders should be encouraged. Even as new technologies develop for automated ocean plankton measurement the CPR will be needed for parallel running with them for the foreseeable future.

  d. The **Atlantic Meridional Overturning Circulation Array (AMOC) at 26°N** consistently viewed as of global significance and high priority throughout the consultation. The array has been rigorously optimised; efforts to introduce new technologies and recover data more in real-time should be encouraged.

  e. The **Ellett Array** is high priority because it provides the UK's eastern boundary contribution to the 'Overturning in the Subpolar North Atlantic Programme (OSNAP). The Ellett Array was commended by the Panel in pioneering as a demonstrator use of continuous sea-glider transects instead of research ships. Configuration of Ellett array will be part of any optimisation of the OSNAP array as a whole and is of regional interest.

  f. The **UK contributions to the Global Sea Level Observing System (GLOSS)** are high priority part of the Global Sea Level Observing System, complementing and calibrating satellite altimeters by measuring at mid-ocean locations. UKRI-NERC funding supports high accuracy and remotely controlled oceanic island gauges in the South Atlantic and Southern Oceans. UKRI-NERC funding does not currently support GLOSS gauges in the UK (operated for flood warning by the Environment Agency) and have not been providing climate quality for five years data. There is a question as to whether a modest UKRI-NERC funding to support scientific quality control would be of benefit. Synthesis of the global mean sea level data set is also being undertaken without UKRI-NERC support but is at risk of having to cease, leading to retreat from a UK global leadership position.

- **SIX** - The WCO, PAP and AMT deliver sustained observations as well as being 'platforms' for other science projects, technology trials and demonstrations - important added benefits. However, this means some of these systems (especially WCO and PAP) have almost unlimited scope for growth that may not have been adequately tensioned against the full portfolio of sustained ocean observations needed. Consequently, greater clarity is needed as to what is their optimal scale of operation is within available resources including (i) the irreducible core observations needed and (ii) savings and efficiencies achievable through changing intensity and frequency of sampling.

- **SEVEN** – The repeat survey of three UK MPAs that have experienced seabed disturbance (two in deep water provinces) has only recently been brought into classification as sustained observing (supporting the international strategy of diversifying into more ecological observations). Whilst the Panel considered the science unique with strong UK leadership, online survey respondents found it harder to discriminate the relative balance of science and regulatory monitoring and this should be clarified. In line with the opinion offered by the Panel, the time-intervals between repeat sampling and its spatial coverage (possible need to increase both) should be reviewed to increase sampling effectiveness.

- **EIGHT** - There were no suggestions for new sustained observations; the following are recommended:

  a. Visibility and communication of these observations and their value should be improved within the scientific community and beyond;

  b. Data discoverability and accessibility of sustained observations should be improved;

  c. Continuous sampling using continuous sea-glider lines is a possible new sustained observing activity building on experiences of the pioneering Ellett array and ideally suited to

  d. bridging the data gap between the deep sea (Argo) and the continental shelf.

  e. Improved coordination with other non-scientifically motivated marine observations;

  f. Strengthen, at UK and international levels, the science-policy interface with respect to the data and information uniquely generated by systematic, sustained ocean observations.

GENERAL RECOMMENDATIONS (FUNDING)

18. Whilst consideration of cost is excluded from this report, the costs of the systems vary, with less than eleven making up the larger proportion of the total funding envelope.

- **NINE** - Costs should be collated in a consistent and comparable form for the observation systems considered. Charting where observations sit within a matrix of scientific need/effectiveness versus cost would help deciding how to balance future investments.

- **TEN** - It would be desirable for funding for tightly defined sustained ocean observations to be consolidated into the UKRI-NERC National Capability funding stream (given its purpose in relation to scale, duration of science, and expectations for delivery and accessibility). However, care would be needed to avoid the risk of unintentionally causing perverse outcomes that could outweigh the benefits (e.g., the relative balance of ship, capital, and science operating cost expenditure).

- **ELEVEN** - Capital (CAPEX) and operational (OPEX) and Research Ship Usage (USER-COST) funding lines should aligned more consistently to understand costs and benefits.

CONCLUSIONS

19. The Panel commended UKRI-NERC for recognising the importance funding systematic sustained ocean observations as part of its research portfolio and for reviewing observations to test their need and scientific value. Others could learn and adopt practices from the exercise.

20. The international backdrop for consideration of sustained ocean observations is the growing recognition of the need to expand the geographical, depth and Essential Ocean Variable coverage of ocean observations. This is in line with the Global Ocean Observing System 2030 strategy and envisaged by the UN Decade of Ocean Science 2021-2030 which identifies the need to 'ensure a sustainable ocean observing system across all ocean basins that delivers accessible, timely and actionable data and information.'

21. The central conclusion from the consultation was that all that the core of observations described – which are those left after previous reprioritisation efforts - are making important contributions to science. No strong case has emerged to cut any completely (though ocean surface carbon measurement needs to rapidly develop a different approach). Nevertheless, the consultation raised questions about whether all need to be delivered at the scale or frequency at which they are currently operating. Some systems are also performing functions as wider science platforms above and beyond the function of observations in the strict sense. This may give some flexibility in considering whether these aspects might be more appropriate for funding under different budget headings.

22. The opportunities for innovation are significant as autonomous technologies offer the opportunity to transition some systems into new modes of operation (some are already pioneering this and it is important lessons are shared). However, autonomous technologies are not the answer to everything and throw up the challenge of ensuring data quality for sensors (many in development stage) which will be left unattended for years in the ocean. Consequently, there will be a need in transitioning ocean sensing systems extended duration (up to a decade or more from the learning experience of Argo) parallel running using established methods and high accuracy ship-based measurements where absolute calibrations with seawater samples are possible.

REFERENCES

Aiken, J., *et al*. (2017). A synthesis of the environmental response of the North and South Atlantic sub-tropical gyres during two decades of AMT. Progress in Oceanography 158, 236-254. doi:10.1016/j.pocean.2016.08.004

Amaro T., *et al.* (2016) The Whittard Canyon – A case study of submarine canyon processes. Progress in Oceanography, 146, 38-57.

Benoist, Noëlie M.A. *et al*. (2019) Monitoring mosaic biotopes in a marine conservation zone by autonomous underwater vehicle. Conservation Biology, 33 (5). 1174-1186. https://doi.org/10.1111/cobi.13312

Buch E. *et al.* (2019) Sustainability Survey [on-line] Available at: Sustainabilitysurveyupdatedreportfinal.pdf (copernicus.eu) & referred to in Sustainable funding for ocean observations | European Marine Board

EMB (2021) Policy Brief: Sustaining in situ ocean observations in the age of the digital ocean

Frajka-Williams E, *et al*. (2019) Atlantic Meridional Overturning Circulation: Observed Transport and Variability. Front. Mar. Sci. 6:260. doi: 10.3389/fmars.2019.00260

Government of Canada (2018) Charlevoix blueprint for healthy oceans, seas and resilient coastal communities

Hartman, S., *et al*. (2021). The Porcupine Abyssal Plain sustained observatory (PAP-SO) in the North East Atlantic. Progress in Oceanography. Special Issue.

Hirschi, J-M, *et al*. (2020). The Atlantic Meridional Overturning Circulation in High-Resolution Models. Journal of Geophysical Research: Oceans, 125, (2020) https://doi.org/10.1029/2019JC015522

Hoegh-Guldberg, O. *et al*. (2015). Reviving the Ocean Economy: the case for action - 2015. WWF International, Gland, Switzerland., Genevea, 60 pp.

Hoegh-Guldberg. O., *et al*. 2019. "The Ocean as a Solution to Climate Change: Five Opportunities for Action." Report. Washington, DC: World Resources Institute. Available online at http://www.oceanpanel.org/climate

Intergovernmental Oceanographic Commission (IOC) (2019) The Global Ocean Observing System 2030 Strategy. IOC Brochure 2019-5 (IOC/BRO/2019/5 rev.

IPBES (2019): Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES secretariat, Bonn, Germany. 1148 pages. https://doi.org/10.5281/zenodo.3831673

IPCC (2019) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. https://doi.org/10.1017/9781009157964.

IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

Jevrejeva, S. *et al*. (2019): Probabilistic Sea Level Projections at the Coast by 2100. Surveys in Geophysics, 40(6), 1673–1696, doi:10.1007/s10712-019- 09550-y *In* IPCC (2021) Climate Change: The Physical Science Basis

Jevrejeva, S., *et al*. (2020): Global mean thermosteric sea level projections by 2100 in CMIP6 climate models. Environmental Research Letters, 16(1), 14028, doi:10.1088/1748-9326/abceea *In* IPCC (2021) Climate Change: The Physical Science Basis.

Li, F. *et al*. (2021) Subpolar North Atlantic western boundary density anomalies and the Meridional Overturning Circulation. Nature Communications, 12 (1), 3002 (2021). https://doi.org/10.1038/s41467-021-23350-2

National Oceanography Centre, *et al*. (2021) NZOC: Net Zero Oceanographic Capability Summary Report

National Research Council (2011) Critical Infrastructure for Ocean Research and Societal Needs in 2030. https://nap.nationalacademies.org/read/13081/chapter/1

OECD (2015), Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development, The Measurement of Scientific, Technological and Innovation Activities, OECD Publishing, Paris. DOI: http://dx.doi.org/10.1787/9789264239012-en

OECD (2016) The Ocean Economy in 2030, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264251724-en

Organisation for Economic Co-operation and Development (OECD) (2016a) Development Co-operation Report 2016 - The Sustainable Development Goals as Business Opportunities

Smyth, T., *et al*. (2015). The UK Western Channel Observatory: Integrating pelagic and benthic observations in a shelf sea ecosystem Progress in Oceanography Special Issue Volume 137, Part B.

UN (2021). The Second World Ocean Assessment (volumes 1 and 2) United Nations publication no.: E.21.V.5 ISBN: 978-92-1-1-130422-0

von Schuckmann *et al*. (2020) Heat stored in the Earth system: where does the energy go? Earth System Science Data, 12 (3). 2013-2041. https://doi.org/10.5194/essd-12-2013-2020

Tilbrook, B; et al. (2019) An Enhanced Ocean Acidification Observing Network: From People to Technology to Data Synthesis and Information Exchange. Frontiers in Marine Science 6., 19 June 2019 Sec. Ocean Observation https://doi.org/10.3389/fmars.2019.00337

United National Office for Disaster Risk Reduction (2015) (UNISDR) annual report 2015

UKRI (2022) How Research England supports research excellence

UNESCO (2017) Global Ocean Science Report 2017 & Global Ocean Science Report 2020

FIGURES

4: EMB (2021) Image adapted from Virapongse, et al. (2020). Ten Rules to Increase the Societal Value of Earth Observations. Earth Science Informatics 13(2): 233-47. CC-BY 4.0 https://creativecommons.org/licenses/by/4.0/

5: Tanhua T. *et al.* (2019) What We Have Learned From the Framework for Ocean Observing: Evolution of the Global Ocean Observing System. Front. Mar. Sci. 6:471. doi: 10.3389/fmars.2019.00471 Licence: https://creativecommons.org/licenses/by/4.0/

6: NOCA (2013) Scanning the Horizon [on-line]

7: Ocean-ops.org (2022) (The Global Ocean Observing System: 'system of systems' (OceanOPS Integrated - generated 22-08-6).

8: 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 Creative Commons – Attribution 3.0 IGO licence.

9: OSPAR (2010) Jurisdictional zones of the United Nations Convention on the Law of the Sea, the OSPAR Convention, the EU Water Framework Directive and the EU Marine Strategy Framework Directive.

10: Evans, A. World map showing 200 nautical mile limits of national jurisdiction.

13: UNESCO (2017) Ocean science citations scaled as country size In Global Ocean Science Report – The current status of ocean science around the world, L. Valdés et al. (eds), UNESCO Publishing, Paris. (Creative Commons — Attribution-ShareAlike 3.0 IGO — CC BY-SA 3.0 IGO)

16: NOC/P.Brown & V. Byfield (2010) Schematic of the Atlantic Meridional Overturning Circulation (AMOC) with concentrations of anthropogenic carbon concentrations at 24.5°N in 2010.

17: Ocean-ops.org (2023) The global OceanSITES array.

19: AMT legs undertaken on research ship passage legs to the South Atlantic (mostly polar research/supply ships. Image taken from AMT Cruise 30.

21: Argo (2023) The global array of Argo profiling floats. These data were collected and made freely available by the International Argo Program and the national programs that contribute to it. (https://argo.ucsd.edu, https://www.ocean-ops.org). The Argo Program is part of the Global Ocean Observing System. Argo (2023). Argo float data and metadata from Global Data Assembly Centre (Argo GDAC) – Snapshot of Argo GDAC of May 2023. SEANOE. https://doi.org/10.17882/42182#102270

23: Campbell, M. et al. (2021) The UK contribution to Global Alliance of CPR surveys is the North Atlantic Testing Bergmann's rule in marine copepods. Ecography. 44. 10.1111/ecog.05545. Licence: https://creativecommons.org/licenses/by/3.0/

25: Ocean-ops.org (2019) The GO-SHIP global array of core lines

27: Holliday, P., (2015) The Ellett Array presently represents the UK contribution of eastern part of the OSNAP multi-national subpolar North Atlantic array.

29: Ocean-ops.org (2022) The Global Ocean sites network – PAP is one of a small number of interdisciplinary mooring sites contributing to Ocean Sites

31: The global GLOSS network of coastal and oceanic island tide gauges – the UK contributions are around UK coast (Environment Agency) and South Atlantic oceanic islands and Antarctica (UKRI-NERC) Credit PSMSL

33: WCO (2022) Western Channel Observatory sampling stations

34: Tilbrook, B; *et al.* (2019) An Enhanced Ocean Acidification Observing Network: From People to Technology to Data Synthesis and Information Exchange. Frontiers in Marine Science 6., 19 June 2019 Sec. Ocean Observation https://doi.org/10.3389/fmars.2019.00337

Licence: https://creativecommons.org/licenses/by/4.0/

37: JNCC (2018) UK Territorial Sea Limit. UK Exclusive Economic Zone. UK Continental Shel (Designation of Area) Order 2013. Licence: https://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/

APPENDIX 1

Two approaches for deciding what to measure over the long-term, depending on the purpose of the observations.

A. AGREED ESSENTIAL OCEAN VARIABLES (EOV) – GLOBAL OCEAN OBSERVING SYSTEM

Purpose is to characterise and understand processes, change and variability in the ocean system.

PHYSICS - Sea state, ocean surface stress, sea-ice, sea surface height, sea surface temperature, sub-surface temperature, surface currents, sub-surface currents, sea surface salinity, subsurface salinity, ocean surface heat flux.

BIOGEOCHEMISTRY Oxygen, nutrients (e.g., nitrate, nitrite, phosphate, silicate, ammonia), inorganic carbon, transient tracers, particulate matter, nitrous oxide, stable carbon isotopes, dissolved organic carbon.

BIOLOGY & ECOSYSTEMS Phytoplankton biomass and diversity; zooplankton biomass and diversity; fish abundance and distribution; marine turtles; birds, mammal abundance and distribution; hard coral cover and distribution; seagrass cover and distribution; macroalgal canopy cover and composition; mangrove cover and composition; microbe biomass and diversity, invertebrate abundance and distribution.

B. EXAMPLE OF MARINE ENVIRONMENTAL MANAGEMENT DESCRIPTORS AND INDICATORS

Purpose is to assess effectiveness of measures taken to deliver of a policy aim (in this achievement and maintenance of 'Good Environmental Status' as set out in the European Marine Strategy Framework Directive, MSFD) – some essential ocean variables may contribute to informing the indicators below.

DESCRIPTOR 1: BIODIVERSITY IS MAINTAINED (FISH, MAMMALS, BIRDS, PELAGIC, BENTHIC)

Indicators: Distributional range; Distributional pattern within range; population abundance; population biomass; populations demographics; composition and relative proportions of ecosystem components; condition of the typical species and communities; relative abundance and biomass (pelagic habitats); physical, hydrological & chemical conditions; multi-metric indexes assessing benthic community condition and functionality; benthic habitat area.

DESCRIPTOR 2: NON-INDIGENOUS SPECIES DO NOT ADVERSELY ALTER THE ECOSYSTEM

Indicators: Trends in abundance, temporal occurrence and spatial distribution in the wild of non-indigenous species; impacts of non-indigenous invasive species at the level of species, habitats and ecosystem.

DESCRIPTOR 3: THE POPULATION OF COMMERCIAL FISH AND SHELLFISH SPECIES IS HEALTHY

Indicators: Fishing mortality; Ratio between catch and biomass index; Spawning stock biomass; Biomass indices.

DESCRIPTOR 4: ELEMENTS OF FOOD WEBS ENSURE LONG-TERM ABUNDANCE AND REPRODUCTION (FISH, MAMMALS, BIRDS, PELAGIC, BENTHIC)

Indicators: Performance of key predator species using their productivity; large fish by weight; abundance trends of functionally important groups/species; population condition based on specified species by-catch; abundance trends of

functionally important groups/species.

DESCRIPTOR 5: EUTROPHICATION IS MINIMISED

Indicators: Nutrients in the water column; chlorophyll concentration in the water column; water transparency related to increase in suspended algae, where relevant; abundance of opportunistic macroalgae; species shift in floristic composition, benthic to pelagic shifts, harmful algal bloom events; abundance of seaweeds and seagrasses impacted by decrease in water transparency; dissolved oxygen changes due to organic matter decomposition and size of area concerned.

DESCRIPTOR 6: THE SEA FLOOR INTEGRITY ENSURES FUNCTIONING OF THE ECOSYSTEM

Indicators: Type, abundance, biomass and areal extent of relevant biogenic substrate; extent of seabed significantly affected by human activities for different substrate types; multi-metric indexes assessing benthic community condition and functionality.

DESCRIPTOR 7: PERMANENT ALTERATION OF HYDROGRAPHICAL CONDITIONS DOES NOT ADVERSELY AFFECT THE ECOSYSTEM

Indicators: Extent of area affected by permanent alterations; Spatial extent of habitat affected by the permanent alteration.

DESCRIPTOR 8: CONCENTRATIONS OF CONTAMINANTS GIVE NO EFFECTS

Indicators: Concentrations of designated contaminants in relevant matrix (biota, sediment, water); levels of pollution effects on ecosystem components; occurrence, origin (where possible), extent of significant acute pollution events.

DESCRIPTOR 9: CONTAMINANTS IN SEAFOOD ARE BELOW SAFE LEVELS

Indicators: actual levels of contaminants detected and number which exceeded regulatory levels; frequency of regulatory levels being exceeded.

DESCRIPTOR 10: MARINE LITTER DOES NOT CAUSE HARM

Indicators: Trends in the amount of litter washed ashore and/or deposited on coastlines; trends in the amount of litter in the water column (surface and sea floor).

DESCRIPTOR 11: INTRODUCTION OF ENERGY (INCLUDING UNDERWATER NOISE) DOES NOT ADVERSELY AFFECT THE ECOSYSTEM

Indicators: Days and distribution in which anthropogenic sound sources exceed specified levels; trends in the ambient noise level as specified.

APPENDIX 3

THE SURVEY - OVERALL PERSPECTIVE

1. Which most closely describes your involvement with sustained ocean observations?
    - involved in making sustained ocean observations;
    - involved in developing or producing equipment for sustained ocean observations;
    - use data from sustained ocean observations;
    - use advice, assessments or information derived from sustained ocean observations;
    - have a general interest in sustained ocean observations.
2. Which most closely describes your overall opinion of sustained ocean observations?
    - Important for providing evidence to manage the marine environment, risks and resources.
    - Important for addressing fundamental science questions concerning long-term, large-scale change and variability in the ocean.
    - Provide useful background information for other more specific short-term observations.
    - Research investment should focus on grants not on sustained ocean observations.
    - It seems mostly like observing for the sake of observing.
    - Should always meet a UK policy need not just be for answering science questions.
    - UK has responsibility to contribute to global observing efforts as a good global citizen.
    - UK should focus its observing efforts on understanding and managing UK seas.
    - Investment should focus on finding ocean solutions not on ocean observing.
    - Ocean observing is needed alongside solutions to design and inform them with evidence.
3. To what extent do you agree that the following criteria should be used by UKRI to decide the importance of which sustained ocean observations to fund?
    - Whether the observations have a primary scientific motivation.
    - The quality of science supported by the observations.
    - Whether the observations need to be long-term and large scale to address the question.
    - Whether there are alternatives to in water observations to obtain the necessary data.
    - Whether the observations contribute to agreed international plans for GOOS.
    - Whether it could be reputationally damaging not to contribute to an agreed observing plan.
    - The uniqueness of the UK's contribution via the particular sustained observation system.
    - Whether the observations contribute to wider societal benefit.
    - Accessibility to data from the sustained observations.

    - The international scientific significance of the sustained observations.
    - The significant for the UK and UK nations of the sustained observations.
    - The extent of international scientific use of data from the sustained observations.
4. To what extent do you feel that the following are currently accurate?
    - The data generated by the observations are openly accessible in a timely fashion in line where possible with FAIR principles (Findable, Accessible, Interoperable, Re-usable).
    - The observations have wider demonstrable impact beyond science in supporting co-benefits of information and evidence ocean policy, assessments, actions and solutions.

SPECIFIC OBSERVING SYSTEMS - QUESTIONS ASKED ABOUT EACH OBSERVING SYSTEM:

5. Which of the following do you think the observations are most relevant to?
    - Physical aspects of climate change and variability e.g., temperature, circulation, sea level
    - Global carbon cycle
    - Marine ecosystems
    - Natural hazards and extremes
    - Sustainable use of marine resources
6. Which Ocean Decade societal outcomes do you think the observations most apply to?
    - A clean ocean
    - A healthy and resilient ocean
    - A predicted ocean
    - A safe ocean
    - A sustainable harvested ocean
    - A transparent ocean
7. What do you think is the primary motivation for these observations?
    - Research (i.e., pushing the frontiers of knowledge and understanding)
    - To fulfil a regulatory or similar need for monitoring the state of the marine environment
    - To support an operations service like weather forecasting or flood warning
8. Please indicate the extent to which you agree or disagree with the following statements. These observations:
    - Address a current well-posed scientific question of major scientific significance.
    - Are having a demonstrable scientific impact in advancing knowledge and understanding.
    - Are capable of adapting to addressing multiple scientific questions over an extended duration into the future.
    - Are no longer needed because the question they set out to address has changed or been answered.
    - Seem like observing for observing's sake with no clear research question in mind.

9. Why is long duration justified as a methodology in this case? (Select up to three)
    - The observation is investigating inherently large-scale, long-term processes.
    - Is chance something interesting will be found if measurements continue for long enough.
    - The observation is investigating processes where the signal to be detected is small compared to background variability.
    - The observation is investigating processes where the signal to be detected is intermittent/episodic over long durations.
    - The observation supports an operational service.
    - The observation supports regularly repeated state of the environment assessments.
    - Other, please specify.
10. Please indicate how strongly you agree or disagree with the following statements about the duration of the observations. The observations should:
    - Continue indefinitely.
    - Continue for at least 10 years to address significant outstanding science questions.
    - Transform into an operational service or routine monitoring activity within the next five years.
    - Transform into an operation service or routine monitoring activity in the medium term (> five years).
    - Transform into or statutory monitoring activity relatively soon (e.g., within five years).
11. The observations primarily concern processes operating at which of the following space scales?
    - global scale
    - ocean basin scale
    - regional or national scale
    - local scale – e.g., marginal sea or smaller
12. Why is the UK contribution to these sustained ocean observations important?
    - The location is representative of a broad biogeographical or other oceanographic province which would otherwise not be represented at the global level ocean sampling without this UK contribution.
    - The locations only accessible by the UK and without these observations there would be a gap in geographical coverage at important scales in an internationally agreed sampling programme.
    - The observations are primarily relevant to processes taking place around the UK or a specific locality in the UK.
    - The observations are of very long duration and are unique or distinctive for that reason.
    - The observations are a UK contribution to a globally standardised set of observations to which many nations (> 20, say) are contributing and lack of contribution from the UK would be seen as not contributing to global efforts.
    - The UK has a unique or distinctively strong contribution to make to these observations.
13. Select all areas of opportunity for significant technological innovation in terms of this observation within the next five years.
    - Enhance the volume and quality of data generated.
    - Provide significant advance towards net zero oceanographic capability.
    - Reduce the cost of existing observations.
    - Mean these observations are no longer needed.
14. Do you wish to add an additional sustained observing system? If so, describe.

FUNDING CHALLENGES FOR SUSTAINED OCEAN OBSERVATIONS.

15. How strongly to you agree or disagree with the following statement?
    - Funding for sustainable in situ ocean observations is especially challenging maintain.
16. What are your main reasons for this assessment? (Select as many as apply)
    - Funding agencies do not like long-term financial commitments.
    - Sustained ocean observations too heavily rely on research project funding.
    - Many would prefer funding spent on research grants not tied up with long-term observing.
    - There are no operational agencies with institutional funding to support ocean observations.
    - Long term observations are of little value in the ocean.
    - There are few users of data from long term ocean observations.
    - The case for long-term ocean observations has not been made clearly enough.
17. If you believe that funders *other* than UKRI should *primarily* be funding these, please list them.
18. If you believe it would be possible to reduce cost either by scaling them back, making them less frequently or measuring them in other ways, please explain.

CONTRIBUTING ORGANISATIONS – 189 RESPONSES

UK Research Institutes	**Total**
British Antarctic Survey	5
British Oceanographic Data Centre	4
National Oceanography Centre	55
Marine Biological Association	2
National Centre for Atmospheric Science	2
Plymouth Marine Laboratory	18
Scottish Association for Marine Science	9
	95
UK Universities	
Heriot-Watt University	1
University of Bristol	1
University of Exeter	4
University of Glasgow	2
University of Leeds	2
University of Liverpool	6
University of Plymouth	9
University of Reading	1
University of Southampton	3
	29
Government Agencies and organsations	
Bluefin Tuna UK	1
Centre for Environment, Fisheries and Aquaculture	3
Environment Agency	1
Marine Scotland Science	2
Marine Environmental Data and Information Network	2
Met Office	9
Seasearch c/o Marine Conservation Society	1
Nortek UK	1
	20

International universities and institutes	
Alfred-Wegener-Institut	2
European Multidisciplinary Seafloor and water-column Observatory (EMSO) European Research	2
Federal Maritime and Hydrographic Agency	1
French National Centre for Scientific Research (CNRS)	2
GEOMAR Helmholtz Centre for Ocean Research Kiel	1
Hellenic Centre for Marine Research	1
Institut Ruder Boskovic	1
Institute for the Fisheries and Oceans, University of Briti	1
Instituto Español de Oceanografía	1
Maynooth University Ireland	1
Mediterranean Institute of Oceanography, CNRS	1
Mercator Ocean International	1
National Center for Atmospheric Research	1
National Marine Fisheries Research Institute	2
NOAA/Geophysical Fluid Dynamics Laboratory	1
NORCE Norwegian Research Centre	1
Royal Belgian Institute of Natural Sciences	2
University of Bremen	1
Université Jean Lorougnon Guédé Daloa	4
University of Miami	1
University of Papua New Guinea	3
University of Vigo	1
	32
Other	
Anonymous	9
Retired	3
Several conservation and environmental orgs.	1
	13
Total	**189**

APPENDIX 4

Free text opinions expressed by online survey respondents.

QUESTION: WHAT DO YOU THINK IS THE PRIMARY MOTIVATION FOR THESE OBSERVATIONS?

- **AMOC**
    - 'critical to understanding the ocean's role in climate and have policy and practical implications as changes in AMOC affect storm tracks, rainfall, sea level, etc...'
    - 'fact checker--are paleo indicators reliable? do coupled climate models realistically simulate climate change'.
    - 'meet both a direct research need, but also inform many climate models which will inform adaptation planning, globally and in the UK'.
    - 'provides information on the ocean role in decadal/centennial climate variability, with an emphasis on North Atlantic/European regions. Motivation is thus to improve climate prediction on these timescales (reduce uncertainty in projections).
    - 'The care of ecosystems, the quality of the general environment and the renewal of humanity (values, attitudes and actions) are interconnected and integrated and must be addressed simultaneously for their mutual support. Ref.: Pilon, A. F., Restoring the Relationship between People and the Earth: Environment, Politics and Governance / Restaurer les Relations entre les Hommes et la Terre: Environement, Politique et Gouvernance [on line]: https://www.researchgate.net/publication/353130658_Restoring_the_Relationship_between_People_and_the_Earth_Environment_Politics_and_Governance
    - 'It is the first basin wide observational evidence ever of the global ocean conveyor belt'.
    - Global climate change and significant regional climate change in Europe and N. America
    - 'Serve multiple purposes: research, policy, operations. Not one or the other'.
    - Research - but also key to understanding decadal and longer scale climate change.
    - 'Measuring a key indicator of the state of the Atlantic Ocean. This has important implications for predicting the future evolution of the Atlantic with impacts on the physical climate system, carbon cycle, and marine ecosystems'.
- **AMT**
    - AMT is fundamentally opportunistic and not justified via any strategic scientific approach.
    - Multi-purpose - research, climate change, healthy ecosystems
- **ARGO**
    - 'Multiple benefits ranging from improved understanding and prediction of ocean climate change (including the carbon cycle) and for shorter term ocean predictions/forecasts'.
    - As a vital contribution to the GOOS [Global Ocean Observing System] and the GCOS [Global Climate Observing System]
    - All three reasons, research forecasting and monitoring
    - A combination of research and operational oceanography. The primary use varies by country (based on national funding streams) and Argo contributes to both.
    - Multi-purpose. Research, climate change, state of the oceans
    - Good example of having (at least) dual purpose of operational and research.
- **CPR**
    - To monitor changes in ocean primary production to support fisheries management and ocean forecasting with climate change.
    - Research and to fulfil regulatory monitoring are equal motivations for CPR observations.
    - Multi-purpose - marine biodiversity, climate change, ecosystems, pollution
- **GO-SHIP**
    - A top-quality reference dataset to calibrate/validate the other systems.
    - GO-SHIP provides ocean observations of the highest accuracy/quality, that also serve as a necessary reference for other observing networks (e.g., One Argo)
    - As a vital contribution to GOOS and GCOS
    - All three - research monitoring and forecasting
- **ELLETT ARRAY**
    - The expansion for OSNAP [Overturning of the Subpolar North Atlantic Programme] has pushed the research side, but the sustained aspects of identifying trends in ocean climate for monitoring and assessment processes, to inform climate adaptation planning, globally and within the UK.
    - Research, monitoring and forecasting
- **PAP**
    - Understanding biological processes in the context of physical processes
    - Multipurpose. Research, climate, biodiversity, marine ecosystems
    - Research but also to capture long term changes and episodic events (using time series and near real time data).
- **GLOSS**
    - As part of a global observing system, with relevance to UK
    - Monitoring sea-level change, which is one of the greatest threats to populations associated with global climate warming.
    - They have a dual function: (1) supporting operational forecasting and (2) supporting longer term predictions associated with climate change.
    - Research & Support operations services (1st and 3rd items).
    - The observations are critical to our understanding of observed sea-level rise and coastal flood hazard. Coastal flood hazard is the top environmental phenomenon in the UK Govt Risk Register and understanding both current and future flood hazard is critical to UK adaptation planning.

- **SOO-C**
    - Contribution to global observing systems for GOOS and GCOS. GOOS [Global Ocean Observing System and the Global Climate Observing System]
    - Part research and part long time series - with potential for operational monitoring (e.g.: most of the UK SOOPs [Ship of Opportunity Programmes] go through UK waters). Commercial SOOPs are low-cost platforms - Research vessels could also be used more as SOOPs

QUESTION: WHY IS LONG DURATION JUSTIFIED AS A METHODOLOGY IN THIS CASE?

- **AMOC**
    - for the management of ecosystems, we need to know when change is happening. On land we have continuous measurements for weather, species distribution etc. The oceans comprise 70% of our planet's [surface] yet we still don't know much.
    - Observations help inform which hurricane seasons in the Atlantic are related to a slowdown in the AMOC.
    - We cannot yet tell how much is anthropogenic signal and how much internal variability, yet both these components are signals we need to understand. A key motivation not given as choice above is risk assessment. The consequences of a major AMOC change could be devastating for the UK, Europe and many other regions of Earth. These observations are the only direct evidence we have for AMOC changes and provide a key piece of 'ground truth' for attempts to estimate AMOC changes from other, indirect indicators.
    - Climate model simulations project a weakening of the AMOC in the coming decades due to climate change. Imperative we monitor the AMOC in the context of these projections - for both scientific understanding and because of wide-ranging implications of associated future impacts.
    - To separate multi-decadal variability from climate change.
    - Slow-down of the NA overturning is a widely predicted outcome of climate change that could be quite non-linear, while long-term variability of the circulation is implicated in natural climate change.
    - The observations are used and needed to evaluate ocean and coupled climate models by providing a unique time series of the Atlantic Meridional Overturning Circulation
    - We still know very little about how the AMOC works, and numerical models generally do a very poor job of capturing it. Improving our understanding, and our modelling, of the AMOC is imperative for accurate climate prediction, and relies upon continued monitoring of its strength and variability over time.
    - The evaluation of and improvement of climate models. Models show that the AMOC is a key driver of UK and European climate, yet its representation is poor in climate models and questions span how coherent AMOC is, and how important variability is on different timescales. This led to the IPCC AR6 saying we have low confidence in past changes in AMOC and its importance. Therefore, it is key to have long observations to understand AMOC in models, and RAPID26N is the longest time-series already available. Therefore, continuing it is crucial.
    - By being long-term the observation can produce a better understanding of ocean health
    - The observations to-date have already shown some unexpected changes but for testing climate models longer-term measurements are required.
    - To understand holistically what is happening in the Atlantic we need long-term observations and models. This time series is a benchmark time series against which model simulations of AMOC are validated, and then used to understand the mechanisms behind AMOC.

- **AMT**
    - Provides crucial training needs for early career researchers.
    - Environment is changing and these observations enable us to observe those changes over time.
    - In a changing climate, the continuous and repeated observation of an environment such as the transect of the AMTs is essential for our basic understanding of the oceans and how they affect life on earth. "One time is no time" where ocean research is concerned.
    - The science is very interdisciplinary, as is the case in cutting-edge oceanographic programs. This cross -fertilization of biology / chemistry / physics greatly increases the overall value of the program to the international scientific community. Long-term sustained observations are of vital importance if high quality - and this is a high quality, consistently measured program.
    - The observation/platform that AMT provides is uniquely basin scale covering multiple oceanic domains from temperate, sub-tropical, tropical and upwelling. Only sustained observation to cover the Atlantic south gyre system.
    - Provides regular opportunity for a wide range of science and supports in particular many PhD students' projects, so contributes a lot to learning and field skill development
    - Investigating key ecological and multidisciplinary questions that can only be addressed using long-term observations.
    - The major strength of AMT (and there are many to choose from) is the platform it offers the community to get to sea.
    - This cruise samples on a transect that is not otherwise regularly sampled.
- **ARGO**
    - The observations provide information about a part of the ocean that we know very little about (i.e., Deep Argo, the intermediate, deep, and abyssal oceans)
    - Argo is such a valuable resource and is used in so many different studies. It has vastly increased the amount of measurements in the ocean.
    - The Argo observations are critical to our understanding of Earth's energy budget and observed sea-level change. They are also critical to seasonal-to-decadal forecasting, ocean forecasting and next-generation operational (coupled) weather forecasts.
    - [Biogeochemical] BGC-Argo has the potential to enable a fully 4-dimensional observational system for the ocean carbon cycle and ecosystems, when integrated with other observational systems such as satellite and surface observations.
    - As noted above, Argo data are the key source of in-situ data required by ocean prediction models, seasonal forecasting models and for monitoring ocean climate change.
    - The more the better
- **CPR**
    - Unique!!!!
    - As the CPR time-series has grown we have realised the data tell us much more about change than the program was started to tell us about. We don't know how many of these 'surprise' issues will come up in the future.
    - Only long-term observation allows one to separate long term trends from short term variation.

- The observation supports assessment of ecological stability/community diversity/ocean productivity/ecological impacts of climate change etc.
- Supports understanding of changes in primary productivity on long time scales
- The technology might be becoming out-dated.

- **GO-SHIP**
    - The measurements contribute to quantification of ocean heat and carbon uptake. They inform policy makers via IPCC [Intergovernmental Panel on Climate Change] reports.
    - GO-SHIP data are a key calibration dataset for other observing systems like Argo.
- **PAP**
    - It supports regional observations by other European countries.
    - Aspects of the PAP (such as Met office and biogeochemical measurements for ICOS) could become operational as an early warning system for the UK.
    - This long-term and comprehensive surface to seabed observation is unique in the world. One other abyssal time series site is managed by MBARI and is to be shut down in the next few years, leaving the Porcupine Abyssal Plain Sustained Observatory as the only site monitoring ocean health from surface to abyssal seabed on the planet.
    - PAP is a reference site of the Global Climate Observing System (GCOS) and so needs to be maintained for the long term.
- **GLOSS**
    - Measurements include Essential Climate Variables, such as sea level height. Really important to measure this accurately.
    - Can act as an early warning system.
- **WESTERN CHANNEL OBSERVATORY**
    - One response but not detailed.
- **SOO-C SHIP OF OPPORTUNITY-CARBON**
    - These key surface ocean CO_2 measurements (which are currently suspended for lack of funding since 2019!!) feed into the Surface Ocean CO_2 Atlas (SOCAT). They inform estimates of ocean CO_2 uptake used by the Global Carbon Budget, that inform the IPCC report and policy makers, at climate conferences such as the Conference of the Parties in Glasgow in November 2021.
    - The ships of opportunity CO_2 observation programme is the main supplier of observations enabling the calculation of the ocean sink for CO_2 and the broad-scale ocean acidification. The UK was the first nation to begin automated ship-of-opportunity observations for CO_2, and the programme supported up to 2018 generated the crucial data showing how CO_2 uptake in the North Atlantic has changed on decadal time scales.
    - Supports climate action and decision making that requires continuous monitoring.
    - Contribution to global CO_2 atlas SOCAT for global CO_2 flux calculations
- **MPA: MARINE PROTECTED AREAS**
    - Uniquely monitor recovery of ecosystems, such as recovery of the Darwin Mounds from bottom trawling. Quite different to observations of undisturbed systems, providing important information on ecosystem resilience useful to marine governance elsewhere.
    - Long-term observations in key areas of unique biodiversity are required to detect meaningful biological responses to anthropogenic effects or climate change.
    - Assess efficacy of management and enforcement against MPA goals and outcomes
    - These MPAs need to be monitored carefully over at least a decade to inform policy on fishing and other surface and sub-surface activities.
    - marine protected areas protect our biodiversity for the future.
    - protects areas to ensure long term sustainability and protection of marine environments.
    - measures the effectiveness of ocean management.

QUESTION: DO YOU WISH TO ADD AN ADDITIONAL SUSTAINED OBSERVING SYSTEM? PLEASE DESCRIBE.

1. More engagement with volunteers and the general public so they become more aware of possibilities and pollutants within their local environments through citizen science projects.
2. As mentioned above only commenting on UKRI funded monitoring (AFBI, Mar Scotland, Cefas and EA monitoring is out of scope)
3. Earth observation (satellite-based observations)
4. Ocean acoustic observation systems (existing and future developments). For example, global seismology network, defence sonar networks, and future seafloor cable-related acoustic oceanographic observations.
5. We should be paying greater attention to the social dimension of ocean sustainability, after all management is about managing human behaviour which impacts the health of our oceans. Should be doing socio-economic and governance surveys.
6. I would advocate for the UK having a sustained observing system covering broadly the same ground as the ones here in the N Sea operating out of Lowestoft. UK observations of Fish and higher trophic levels in the Sea are strong in support of ICES but there is a big gap in the C cycle here, it's an important location and the UK has a big role to play
7. We would like to flag that there is a wide array of observations that fall outside of the UKRI umbrella, but which should dovetail/fall synergistically with the UKRI funded efforts. These include the monitoring by Marine Scotland Science which covers both coastal, shelf sea and deep-sea monitoring, as well as biodiversity and fish stock measurements.

QUESTION: WHAT DO YOU THINK IS THE PRIMARY MOTIVATION FOR THESE OBSERVATIONS?

1. Multipurpose. Research, operations, climate, carbon, ecosystems, biodiversity
2. The climate, biodiversity and justice crises affecting us all.

QUESTION: WHY IS LONG DURATION JUSTIFIED AS A METHODOLOGY IN THIS CASE?

1. Until more opportunities exist for citizen scientists to contribute, there is no way of assessing what other expertise might be available apart from that of the few employed in such research already. new and different ways of thinking could help.
2. Efficacy of policy and management measures.