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Sustaining *in situ* Ocean Observations
in the Age of the Digital Ocean

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This policy brief is the result of an *ad hoc* Working Group established by the European Marine Board to address sustained *in situ* Ocean observations. The list of Working Group members and reviewers can be found on page 15.

Preamble

Ocean observations (Box 1) and the associated data systems are essential for delivering Ocean information for services, science, management and for the UN Decade of Ocean Science for Sustainable Development[1]. There is a growing demand[2] for timely, reliable Ocean observations, which underpin the value chain from sensors, through information and knowledge to public benefit. Ocean information and knowledge based on observations and data improves our understanding of Ocean processes and informs actions to reverse the cycle of decline in Ocean ecosystem health and safeguard a clean, resilient, healthy and productive Ocean. It is needed to govern our use of the marine environment and to support the growth of a knowledge-based, sustainable maritime economy[3].

This document focuses on *in situ* Ocean observations and highlights their benefits, funding and governance challenges, and the investment needed for their transformation and sustainability. It aims to inform national- and European policy makers, funders, and governance influencers; the G7 and G20; and UN agencies such as the Intergovernmental Oceanographic Commission (IOC) of UNESCO.

Box 1: What are Sustained *in situ* Ocean Observations and the Ocean Observation Value Chain?

Sustained *in situ* Ocean observations are all Ocean, seas or coastal observations, which are made primarily for public good (i.e. monitoring), and/or for research of public interest. They complement remote sensing observations (e.g. from satellites) and either persist over extended durations (e.g. decades) or have no planned end-date. Sustained *in situ* Ocean observations target phenomena which have large space-time scales (e.g. the impact of ice melt water from Polar regions), or which need long time-series to detect signals and trends (e.g. the impact of climate change on species distributions). They are continuous in order to detect extremes (e.g. marine heatwaves) or episodic events (e.g. volcanic eruptions) and thus generate long data series and/or repeated observations, used to reassess system state. Ocean observations form the basis of the value chain towards public benefit (Fig. 1). They provide the data used in models and analyses to create information, which is turned into knowledge by resource managers and policy makers and used to enact change as well as advance scientific knowledge and understanding. The value of observations is increased by each step in this chain and there is continuous feedback between all these levels: e.g. new policies will create new observation requirements and new model predictions will show where different observations are needed.

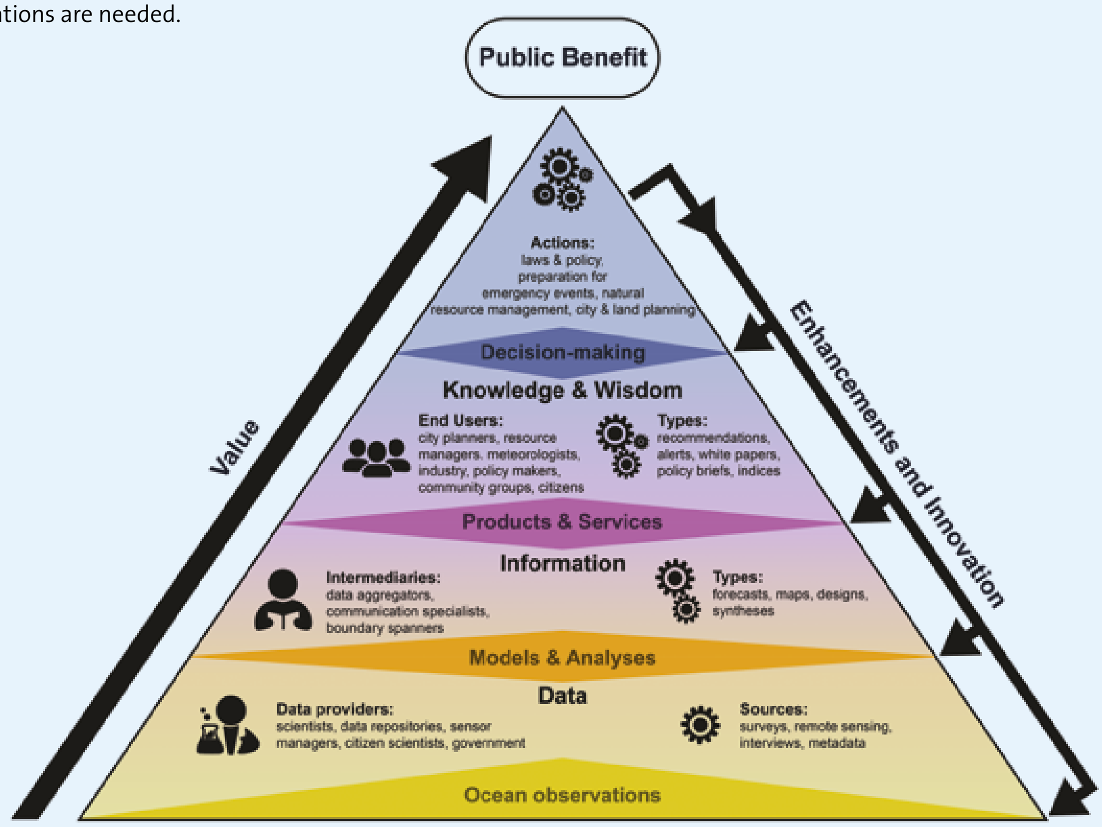

Fig. 1. The Ocean observation value chain[4].

[1] https://www.oceandecade.org/

[2] Setting the Course for Sustainable Blue Planet: Recommendations for Enhancing EU Action https://webgate.ec.europa.eu/maritimeforum/en/frontpage/1469

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

[4] 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/

Buoy on Ostend beach.

In situ observations provide key information about the Ocean environment – its physical, biogeochemical, geological and ecological characteristics. They are essential to monitor critical aspects of the state, change, and variability of the sub-surface Ocean, which comprizes 97% by volume of the global biosphere, takes up and redistributes 93% of excess heat in the Earth system, and absorbs over 25% of all human-produced carbon emissions.

Barriers in existing governance arrangements, limited institutional coordination, and piecemeal funding inhibit the successful, continuous deployment of Ocean observations at the scale required to understand and manage human use of the Ocean. To ensure the long-term stability of Ocean information, the totality of the underlying *in situ* Ocean observing system, comprizing networks of different observing platforms and sensors[5], needs to be recognized as a critical global infrastructure[6]. This mostly publicly funded infrastructure generates openly-accessible data as a global public good from which specific information products and knowledge are created to deliver direct and indirect benefits to society as a whole by informing public policy, governance and business decisions. Such infrastructure needs a strong mandate, including a legal basis to secure binding commitments in a sustained way and in accordance with international standards, including an appropriate data policy for open access and sharing of data. National observing systems and roadmaps should be better aligned and deeper cooperation with regional governing bodies is needed. The required growth of the system urgently needs to be matched with more innovative, holistic and integrative thinking about how to sustainably finance and coordinate these observations.

In situ observations are presently made for diverse purposes, including monitoring for policy (see later) but also for research and innovation (R&I), which is currently the source of much of the funding, albeit on a fixed duration project basis. R&I will benefit from a sustained *in situ* Ocean observation infrastructure, which is needed to address the 'big science' questions of the 21st century such as unprecedented change and variability in the Ocean at global and basin scales with diverse local impacts. To make knowledge-based decisions we need a sustained observing system with a spectrum of funders, implementers, and users; recognising that they bring different strengths to the table, and use the system in different ways. What is missing is a backbone or core of stable investment and institutional coordination to hold the system together, learning from the experience of the 'basic' observing system in meteorology[7].

[5] A system-level view of Ocean Observing system is provided by the Framework for Ocean Observing http://www.oceanobs09.net/foo/FOO_Report.pdf

[6] Public-good infrastructures are economic arteries and veins; i.e. roads, ports, railways, airports, power lines, pipes and wires that enable people, goods, commodities, water, energy and information to move about efficiently and deliver goods and services to citizens, and support the economy, environment and social well-being.

[7] New Global Basic Observing Network https://public.wmo.int/en/media/press-release/new-global-basic-observing-network-gets-go-ahead

Like international R&I collaborative endeavours in high-energy physics and space science, or service providers such as the European Organisation for Exploitation of Meteorological Satellites (EUMETSAT)[8], the Ocean observing system is increasingly dependent on shared, internationally supported infrastructures. For Ocean information, that backbone infrastructure is the system of global Ocean observations, making R&I in particular a prominent user and funder. Special attention is needed to address how to coordinate, mandate and finance large temporal and spatial scale observation infrastructure in the 60% of the Ocean area beyond national jurisdiction, which cannot be achieved solely by the continued, almost exclusive, dependence on short-term R&I project funding.

Benefits of *in situ* Ocean Observations

Sustained, long-term global *in situ* Ocean observations are required to support climate[9] and environmental policies, e.g. the European Green Deal[10], and policies aiming to reach net zero carbon, achieve a sustainable blue economy, protect nature, and reverse the degradation of ecosystems. They are crucial for discovering unexplored parts of the Ocean, and to better observe, monitor and predict the physics, chemistry, biology and geology of the Ocean from global to coastal scales. This is needed to better understand and predict climate change and its impacts on global Ocean ecosystems, increase resilience, develop sound mitigation and adaptation strategies to natural and man-made hazard impacts, and better protect marine ecosystems, among many other uses. These benefits are linked to the need to protect biodiversity, ensure a healthy Ocean and allow a sustainable use of marine resources, which rely on biological observations and need further efforts to be fully integrated into the global Ocean observation system (Benedetti-Cecchi *et al.*, 2018). They generate baseline knowledge informing Ocean governance, Ocean economic opportunities, and sustainable development. *In situ* Ocean observations are also pivotal to improve weather predictions, predict extreme events such as Harmful Algal Blooms, and inform tsunami warning systems, among many others.

Globally, meteorological services are driven by a primary purpose: to deliver weather forecasts to protect lives, property and livelihoods. A report[11] on the value of surface-based meteorological observations (including at the sea surface) makes the case for the development of the Global Basic Observing Network, indicating that this could generate more than USD $5 billion annually, with a benefit-to-cost ratio of 25. As weather and climate predictions extend further into the future, sub-surface Ocean observations will be increasingly necessary[12]. National weather prediction services are coupling atmospheric models to Ocean models – because heat energy that fuels weather systems is stored in the subsurface. The impact of Ocean observations on future weather predictions will therefore require close partnering with meteorological services.

Storms over the Minch, Scotland.

8 https://www.eumetsat.int/
9 https://ec.europa.eu/clima/policies/eu-climate-action_en ; https://unfccc.int/
10 https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
11 The Value of Surface-based Meteorological Observation Data http://hdl.handle.net/10986/35178
12 https://www.ecmwf.int/en/about/media-centre/focus/improving-ocean-observations-better-weather-forecasts

Operational oceanography systems such as the Copernicus Marine Environmental Monitoring Service (CMEMS)[13] integrate *in situ* and satellite observations with model predictions to provide a wide range of Ocean services with large socio-economic impacts such as for maritime transport, fisheries and aquaculture, oil and gas, and marine renewable energy. CMEMS has highlighted the benefits of their services in various use cases, such as tracking marine litter and navigating icy seas[14].

Although the benefits of Ocean observations are difficult to comprehensively identify and value (OECD, 2019; Rayner *et al.,* 2019), a high benefit-to-cost ratio for investing in Ocean observations has been described in several case studies. The JERICO-NEXT project found a high benefit–to-cost ratio (of about five) for the European coastal component of the observing system (Gaughan *et al.,* 2019); and in the United Kingdom, the Marine Environmental Data and Information Network (MEDIN) estimated that the benefit of their data services is eight times the cost invested[15]. While these studies often use different methodologies, leading to results that are difficult to compare, they still demonstrate the positive return on investment. However, more work needs to be done to value the social, economic and environmental benefits of Ocean observations, as many of the societal benefits are also associated with improved science and therefore do not have a readily measurable economic value. It is indisputable that it is necessary to invest in *in situ* observations and satellite constellations to have reliable systems to enable Ocean predictions.

Mandate and Governance of Ocean Observations

There are very different motivations behind Ocean observations, which in turn shape the mandates, institutions and funding arrangements that support them. The strongest mandates for *in situ* Ocean observations occur where national legislation sets requirements to monitor certain environmental ‘indicators’ or specific species; e.g. for the Marine Strategy Framework Directive (MSFD)[16]. European or national regulation drive prioritisation of budgeting for relevant observations to monitor mandated indicators and specific species. Other strong national imperatives that drive sustained funding include public health issues, and protecting people and economic activity against high-probability, high-impact risks such as extreme weather and coastal flooding. Outside the Exclusive Economic Zones (EEZs) of coastal states, the mandates for Ocean observing are weaker. They are tied to international agreements around weather, climate, fisheries, biodiversity and Ocean science agendas and are rarely legally binding. However, many *in situ* systems straddle both legal regimes.

Monitoring cetaceans in the Cretan Sea using an acoustic receiver attached to a glider.

[13] https://marine.copernicus.eu/

[14] https://marine.copernicus.eu/services/use-cases

[15] MEDIN Cost Benefit Analysis 2019 https://www.medin.org.uk/sites/medin/files/documents/MEDIN%20Cost%20Benefit%20Analysis_Final%20Report.pdf

[16] https://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm

Typically, *in situ* Ocean observations developed and maintained through programmatic research funding have proven to be enormously valuable to society and are increasingly relied upon by operational agencies to predict pollution, storm surges, etc. For example, Argo[17] measurements of upper Ocean heat content, and global mean sea level records from coastal tide gauges are both central to the Intergovernmental Panel on Climate Change (IPCC)[18] and inform the United Nations Framework Convention on Climate Change (UNFCCC)[19]. However, they are still primarily supported by R&I projects, not by long-term infrastructure funding. Ocean observations are also imperative for other international conventions, e.g. marine processes and biodiversity observations necessary for the Convention on Biological Diversity (CBD)[20], but that does not necessarily translate into mandates through national legislation. Core funding for these networks needs to be secured through a more sophisticated funding model that recognizes both the research and operational value of sustained Ocean observations.

French Argo floats deployed during the 2017 Reykjanes Ridge Experiment (RREX) cruise (RV *Atalante*) from an Autonomous System for Argo Float Research (ASFAR) structure.

There are interesting similarities and contrasts between the approach to Ocean and meteorological observations and services, which offer learning opportunities. Meteorological observations are diverse – ranging from short-term to seasonal weather forecasts and climate predictions, and extending to atmospheric composition and air quality. Like Ocean observations, not all of these are equally well or sustainably funded. Nevertheless, with weather at the heart of the system, national and regional meteorological services are a clear point of contact for meteorological observations and cooperation standards. Requirements for national commitments to sustain vital observations are supported by the World Meteorological Organisation (WMO)[21] and its legal mandate, the WMO Convention (1950 with subsequent revisions). This kernel of national and international mandates and institutional architecture provides a stable backbone for an operational system based on mature technologies around which other atmospheric observations and innovations can be built. Arguably, Ocean observations are even more diverse, encompassing physical (some overlapping with those of meteorological importance), biogeochemical and biological variables, and with a very diverse range of users interested in the data generated. However, more importantly they lack a well-defined and internationally accepted kernel outside Ocean research.

Rapid technological innovations that have reached certain maturity and reliability have made systematic, sustained Ocean measurements possible that would not have been achievable two decades ago. However, the institutional and funding landscape are yet to catch up with the technological innovations that have made sustained Ocean observations possible. Each country has its own national landscape of institutions responsible for Ocean observations: meteorological agencies, Ocean agencies, the navy, national research agencies, research councils, environmental agencies, national laboratories and academic institutions all play a role. This situation has led to fragility, in particular on the product side of the Ocean observation value chain. More coherent governance, a better-defined core mission, together with a more strategic approach to evolve the observing system would enable more sustained funding to continually observe the Ocean in a smarter way.

17 https://argo.ucsd.edu/
18 https://www.ipcc.ch/
19 https://unfccc.int/
20 https://www.cbd.int/
21 https://public.wmo.int/en

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Glider deployed from the RRS *James Cook*.

International coordination takes place through the Global Ocean Observing System (GOOS)[22]. However, the existing coordination at the global level needs to be supported by clear regional, national and local arrangements, with connections between those coordination structures based on common methods and practices to ensure compatibility and interoperability across scales. Today, GOOS is organised around globally coordinated regional observing systems, and a heterogeneous set of regional alliances established around regional groupings of nations with common interests, such as EuroGOOS[23]. Recently, a number of reviews, projects and coordination activities have focused on the scale of Ocean basins, which seem to be a good scale to engage stakeholders, and to coordinate planning and implementation. There are a number of areas where strengthened coordination is needed and the regional substructures need to be revisited. Examples of these structures are the AtlantOS programme[24], the Southern Ocean Observing System (SOOS)[25], the Indian Ocean Observing System (IOGOOS)[26] and the Tropical Pacific Observing System (TPOS2020)[27]. The connection of these initiatives to GOOS varies, but in many cases has not been sufficiently formalized, and could benefit from clear links and governance.

National Ocean observing systems have been established with varying governance and business models. In the USA, NOAA's Global Ocean Monitoring and Observing (GOMO)[28] funds and coordinates global-scale sustained observations (e.g. Argo) and research projects (more than 60 projects funded); and the USA Integrated Ocean Observing System (US-IOOS)[29] delivers operational observation and prediction capability on the Ocean, coasts, and Great Lakes through a federated regional-national partnership. In Australia, the Integrated Marine Observing System (IMOS)[30] is funded as a collaborative national research infrastructure programme, and managed through an unincorporated joint venture. In Canada, the more nascent Canadian Integrated Ocean Observing System (CIOOS)[31] aims to improve national coordination and collaboration between Ocean data sources and to improve their access and discoverability.

Europe has a substantial capacity in Ocean observations, but maximising the full potential of these investments requires improved coordination, integrated strategies, clear responsibilities and core investment. The system is complex with various levels of organization including European Union (EU) institutions, EU policy drivers, Regional Sea Conventions, European Research Infrastructures (ERICs)[32], infrastructural projects, platform specific networks, thematic issue-based networks, regional and national systems, individual observing systems and platforms. This organically developed approach has led to an overly complex system, with a diverse range of coordination bodies at various levels. The European Ocean observing community is backing the European Ocean Observing System framework (EOOS, Box 2) as a way to help coordinate this complex landscape, and is currently concentrating on coordinating and supporting the funding of *in situ* Ocean observations.

[22] https://goosocean.org/
[23] https://eurogoos.eu/
[24] http://www.atlantos-ocean.org/
[25] http://www.soos.aq/
[26] http://www.iocperth.org/iogoos
[27] https://globalocean.noaa.gov/Research/Tropical-Pacific-Observing-System
[28] https://globalocean.noaa.gov/
[29] https://ioos.noaa.gov/
[30] https://imos.org.au/
[31] https://cioos.ca/
[32] https://ec.europa.eu/info/research-and-innovation/strategy/european-research-infrastructures/eric_en

Box 2: The European Ocean Observing System framework

Recognising the need for strengthened coordination, the European Ocean Observing System framework (EOOS[33]) focuses on all *in situ* Ocean observations in Europe. EOOS aims to align and integrate the existing capacity, promote a systematic approach to collecting information, advocate for a common strategy, set priorities, share data and technology, and exchange expertise and practices. EuroGOOS, the European Marine Board, JPI Oceans and other stakeholders support the implementation of EOOS.

EOOS European Ocean Observing System

An essential element to improved governance is setting up a high-level Ocean observing committee/structure for the systematic coordination of Ocean observing activities at national level. EOOS has advocated for such coordination, and through the current EuroSea[34] project is enabling this coordination through its Operations Committee[35]. EOOS also has a Resource Forum[36], which aims to facilitate coordination and achieve buy-in of funders for Ocean observations.

At EU and regional levels, shared knowledge, data and services have prevailed with the help of European funding. The majority of Ocean observation funding is at the national level and this situation is characterized by complexity (Lara-Lopez *et al.,* 2021), creating a bottleneck and significantly reducing efficiency. The European Commission (EC) has identified this complexity in its consultation on sharing responsibility for Ocean observations[37]. The priority is to direct efforts towards the development of more integrated sustained national systems with clear priorities and strategies, which will have positive impacts on all other levels with a multiplicative effect. Integrated sustained national systems will ensure not only that each observation is used many times, but also that key observations are made at appropriate temporal and spatial scales through a holistic integrated observing system. However, this is not straightforward: while the different legal mandates and imperatives for making and funding observations need to be respected, they should also not be allowed to be a barrier to better integration. We need to find a way to enable strategic and long-term funding for the observation system itself, i.e. for putting equipment in the water and getting the data to shore.

Wave glider in front of the German RV *Sonne.*

33 https://www.eoos-ocean.eu/
34 https://eurosea.eu/
35 http://www.eoos-ocean.eu/eoos-operation-committee/
36 http://www.eoos-ocean.eu/eoos-resource-forum/
37 https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12539-Ocean-Observation

Existing and Improved Funding Models for Ocean Observations

Internationally, evaluating the costs and funding of the observing system is challenging due to differing motivations, running costs, salaries, exchange rates and costing models used across organizations and nations. Some costs (e.g. labour) can vary by a factor of five or more across the world and are typically not comparable[38]. In Europe, the ERICs have precise cost estimates for each infrastructure, the AtlantOS project has provided an estimate of the costs for the Atlantic Ocean Observing Networks[39], and the EC's consultation on Ocean observation has identified that EU member states spend more than 1.5 billion Euro a year on observing the Ocean[40]. However, it is not clear if this is a meaningful number for the cost of all Ocean observations needed in European seas. A more systematic way of extracting these costs is needed.

A holistic and integrated Ocean observing system needs to include a portfolio of observing platforms and capabilities each bringing particular strengths to the integrated observing system (e.g. different niches in terms of space-time-depth and Ocean variable coverage), with very different initial investment and running costs. This system needs long-term planning, with 5-10 year time horizons, as is done with France's Infrastructure funding, the USA's NOAA, Australia's IMOS[41], and the UK's national capability funding[42]. The funding model should include the costs of delivering the data through sustained data streams and enduring data infrastructure that supports research and applications.

In a study on the *in situ* observations underpinning the Copernicus Programme Services[43], Buch *et al.,* (2019) found that only 28% of the Ocean observing networks have sustained funding and 52% are uncertain of their funding in the near future. This is in stark contrast to the high degree of national sustained institutional funding (68%) dedicated to meteorological observations. However, the meteorological services, which mostly fund Ocean surface observations, are on an efficiency drive and *in situ* observing networks for meteorology are not growing.

There is no secure financing for some of the most important sub-surface observations needed to underpin our understanding of climate, biogeochemical and ecological processes, and to provide contextual information of prevailing conditions for other marine monitoring and forecasting services. Currently the European contribution to sustained global scale Ocean observations are often funded through fixed-duration grants, or internationally agreed bi- or multi-lateral joint research project funding, sometimes leading to longer-term commitments on all sides.

Some of the ways funding is obtained for sustained Ocean observations include:

- **Dedicated institutional funding** for national Ocean research, which has an expectation of continuity with grants being reviewed periodically (five years) e.g. Helmholtz Association Programme Oriented Funding, Germany; UK Research and Innovation - Natural Environment Research Council's National Capability Funding; Ministry of Research, Research Infrastructures Roadmap, France;
- **Fisheries surveys,** and their related environmental observations, e.g. coordinated through the International Council for the Exploration of the Sea (ICES)[44] and the General Fisheries Commission for the Mediterranean (GFCM)[45];
- **Capital funding,** which enables procurement of equipment and capitalization of labour costs (e.g. Argo floats procurement);
- **Transitioning from research to operational budgets,** such as the Argo float programme in Germany, which is now funded through the budget of the German Federal Maritime and Hydrographic Agency;
- **Co-funding of dual-purpose observing** infrastructures such as using coastal tide-gauges to support both operational flood warnings and long-term climate trends; and
- **In-kind support from voluntary or opportunistic infrastructures** for which the costs are already being borne by philanthropy and private industry, such as ships of opportunity.

Together, these have greatly enhanced the Ocean observing system in Europe and provide some good practices to be built upon. What is needed is a funding model that significantly improves funding sustainability.

[38] https://tpos2020.org/wp-content/uploads/TPOS-2020-SC-3-Report-2016-12-21-v1-Released.pdf
[39] https://www.atlantos-h2020.eu/download/deliverables/AtlantOS_D1.4_update.pdf
[40] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12539-Ocean-Observation
[41] http://imos.org.au/about/plans-and-reports/plans
[42] https://nerc.ukri.org/research/sites/
[43] https://marine.copernicus.eu/services/use-cases
[44] https://www.ices.dk/Pages/default.aspx
[45] http://www.fao.org/gfcm/en/

Optimizing and Advancing towards an Effective and Efficient Ocean Observing System

An alternative governance and financing model should look to the future and include more creative use of existing funding. **Sustained *in situ* Ocean observations should be supported as an infrastructure delivering Ocean data as a public good,** with funders explicitly developing and using funding models appropriate for infrastructure, not short-term projects. This could include dedicated underpinning capability funding streams created by 'top-slicing' funding before project allocations, using capital funding as capital investments and classifying publicly accessible data infrastructures as capital assets. This funding architecture for sustained *in situ* observations would need to be articulated with scientific project-based Ocean observations, which would continue to be funded by *ad hoc* national and European research programmes (e.g. scientific campaigns resulting in *ad hoc* data collection).

Research funders will inevitably continue to play an important role in global Ocean observations and innovation of new methods. Research funders are especially reticent to increase proportions of spend on fixed infrastructures because it reduces financial flexibility for new projects and innovations (National Research Council, 2011). Nevertheless, it is important to recognize that due to the scale and complexity of the most important questions in Ocean science, it is undergoing rapid transformation into truly global 'big science' – similar to space science and high-energy physics. The way of doing Ocean science is necessarily changing and its core methodology will increasingly depend on data from a shared, globally integrated observing system. Research funders will need to be able to adapt to the transition underway in modern Ocean science.

Where infrastructures already exist with their fixed costs wholly or mainly covered, **marginal additional costs of existing infrastructure should be supported**. Funders should consider the business case benefits of providing funding to cover the additional marginal costs to best exploit these infrastructures, as this can be a significant barrier to their use. Examples include securing scientific data from public infrastructures for hazard warning or marine monitoring; using research vessels for continuous underway measurements (not tied to the existing projects), and as a science/environmental compensation for the carbon footprint of vessels in transit; supporting the use of private infrastructures (ships of opportunity, offshore platforms, subsea cables, etc.); creating tax incentives/reliefs to encourage private industry contributions to marginal costs of their infrastructures for Ocean observations; and formally enabling collection of Ocean observations to be a component of contributions that the maritime sector can make on its trajectory to net zero emissions.

Seal equipped with ocean sensor.

Strengthened coordination is needed across research, operational and monitoring actors, to ensure integration of activities across open Ocean, shelf and coastal environments. Such integration ensures that the combined investment capitalizes on the strengths of these funders and implementers, and delivers more than the sum of its parts to all users. To complement observing obligations within national jurisdictions with international agreements, **commitments to Ocean observations should be linked more explicitly to international agreements**. States make voluntary or other commitments to actions (e.g. climate mitigation, biodiversity preservation). Such a link can ensure that most developed nations make funded commitments to undertake Ocean observations especially in areas beyond national jurisdiction, and contribute to an international fund for Ocean observations by less developed nations.

Global observing costs cannot be borne by national funding systems alone. Some States scale their contributions to what they want to contribute (to meet their own requirements regarding national jurisdictions and some open Ocean R&I) rather than what is actually needed for a globally integrated system. Like other infrastructure-dependent areas of environmental monitoring and research, such as Earth observing satellites and data needed for high-energy physics (Box 3), **an international entity with a subscription-based or binding Nationally-Defined Contributions (NDC) model could be used to sustainably fund Ocean observations**. This funding and governance model should ensure a fully integrated observing system from the coast to the global Ocean. It should recognize the different needs for the global and European observing systems (for which European nations could act together) and for national and EEZ coastal observing systems (implemented by each nation but harmonized and coordinated at European level). The funding model should focus on coordination and funding of pan-European and global observations (outside EEZs, including coordination with countries that share European Seas) and developing an international subscription model and Ministerial-level governance for the core elements of this system that have critical and broad utility. Such a subscription or NDC-based entity would be able to establish the true costs of the global *in situ* Ocean observing infrastructure needed.

Box 3: Examples of International Operational and Research Infrastructure Models

International Space Station (ISS)[46]
A cooperative programme to construct a single low Earth orbiting station. Operated under the International Space Station Intergovernmental Agreement 'IGA' (1998), and several other agreements, the participants are Europe, the United States, Russia, Canada, and Japan. Each partner contributes and owns agreed elements of the space station.

European Council for Nuclear Research (CERN)[47]
A High-Energy Physics research infrastructure at a single physical location straddling Switzerland and France. Governed under the CERN Convention (1953) with 23 mostly European Member States contributing subscriptions as determined by the Convention.

European Space Agency (ESA)[48]
Shaping the development of Europe's space capability including space platforms for scientific purposes and for operational space applications systems. Governed under the ESA Convention (1980), now with 22 European Member States who pay a subscription calculated in accordance with each country's gross national product. There are two Associate Members and Canada participates through a cooperation agreement.

European Organisation for Exploitation of Meteorological Satellites (EUMETSAT)[49]
Through its own satellite programmes, EUMETSAT provides observations and data services for operational weather and Earth system monitoring and forecasting, and for climate services. Governed under the EUMETSAT Convention (1986), it now has 30 Member States which subscribe to mandatory programmes.

World Meteorological Organisation (WMO)[50]
A specialised agency of the United Nations dedicated to international cooperation and coordination on the state and behaviour of the Earth's atmosphere, its interaction with land and Ocean, weather and climate and resulting distribution of water resources. Governed under the WMO Convention (1950), it has 187 Member States and six Member Territories who subscribe to its costs. It oversees observing systems, standards and data exchange for observations provided and funded by the Member States who are required under the Convention to sustain certain critical observations.

[46] http://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/International_Space_Station/
[47] https://home.cern/
[48] http://www.esa.int/
[49] https://www.eumetsat.int/
[50] https://public.wmo.int/en

Integrated design of the Ocean observation system will help to optimize investments. Europe has primarily engaged in observing the Ocean and sea basins around Europe but European investments in the regional and global observing systems must be made in an informed and systematic way, ensuring that national contributions have a lasting impact and are combined with contributions of other nations. This calls for a scientifically rigorous framework to guide the development of an effective and efficient Ocean observing system, for which Observing System Simulation Experiments (OSSEs) and Observing System Evaluations (OSEs) can be used (Fujii *et al.,* 2019). These take into account the synergies and complementarities between satellite and *in situ* observations and the role of modelling and data assimilation. A series of OSSEs carried out as part of AtlantOS[51] have shown that implementing the deep Argo array would reduce uncertainties in the deep temperature and salinity fields by up to 40%, vastly improving our ability to develop forecasts of how the Ocean will respond to (and drive) changing climate. Similarly, an expanding ships of opportunity and mooring network, enhanced by biogeochemical Argo sampling (particularly in the Southern Ocean) and autonomous platforms, should allow a large improvement of the pCO_2 field (and thus of air-sea CO_2 fluxes). Globally consistent coastal and boundary-system data (e.g. using High Frequency radar, fixed moorings, and glider observations) are indispensable to improve the performance of the systems, particularly for developing the scientific underpinning and forecasting capacity required by many stakeholders in the coastal zones (Fujii *et al.,* 2019). Similarly, the Tropical Pacific Observing System 2020 project[52] conducted an in-depth assessment of user requirements, observations requirements (Essential Ocean Variables), observation approaches, and funders' priorities, recognizing that the ultimate 'solution' would be driven by a brokered compromise drawing on the combination of national priorities and drivers. The project also recognized that it would not be successful unless El Niño-Southern Oscillation (ENSO[53]) prediction improved; and persistent systematic errors in models ceased to limit their ability to extract value from the observing system.

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Argo float deployed in the Agulhas Current (as part of the MOCCA project).

[51] https://www.atlantos-h2020.eu

[52] https://tpos2020.org/

[53] El Niño Southern Oscillation https://www.weather.gov/mhx/ensowhat

While Ocean OSEs/OSSEs are useful to evaluate the design and impact of the Ocean observing system, they must be considered as part of a broader evidence base. Incomplete observations must be combined with imperfect models and other relevant information in an optimal manner to improve the observing system and models in order to advance understanding and predictions of the Ocean. Specifically, the integration of biological observation is a priority in view of the need to understand and predict how the ecosystem will change under climate change and other pressures. In addition, it is essential to invest in IT infrastructures, services and partnerships to enable the management of big data applied to *in situ* Ocean observations, and in connection to satellite observations. This would enable sharing of more detailed, accurate and timely knowledge with authorities and citizens across Europe in order to help improve the health of citizens and the environment. The development of Digital Ocean Twins[54] and their application provide additional motivation for a robust Ocean data and information infrastructure. Without sufficient Ocean observations we risk a digital void in the vast volume where the twin subsurface Ocean should be.

Summary and Recommendations

The launch of the UN Decade of Ocean Science for Sustainable Development (2021-2030) provides an opportunity to grow and sustain an Ocean observing system from the coast to the global Ocean, from the surface to the deep sea, and including all its physical, chemical, geological and biological components. This is why it has been specifically identified as one of the ten Decade Challenges. It is essential to improve our understanding of the Ocean system, describe its current state, predict future changes, and provide stakeholders, users and decision makers with the information needed for science based adaptive management. An optimized system should build on and enhance existing capabilities in terms of measured parameters and space/time coverage, taking into account the synergies and complementarities between the different *in situ* networks, satellite observations and their joint model-based analysis.

The development of European contributions to this Ocean observing system requires a much more engaged coordination framework to deliver on common strategies and priorities, align and integrate national capacities, interface with the downstream value chain, conduct cost-benefit analyses, exchange know-how and best practices, and liaise with international activities. To achieve this ambitious goal, national and European policy makers, funders and governance influences will benefit from working with the international community within the framework of the UN Decade of Ocean Science for Sustainable Development, and we recommend they should consider the following actions:

- **Recommendation 1:** Recognize sustained *in situ* observations as a large-scale, essential, and enabling infrastructure generating global public-good data that create information and knowledge-based services, and advance its implementation with appropriate financing models to deliver systematic and long-term monitoring. A possible endpoint could be an international entity with a subscription-based or a binding Nationally-Defined Contributions model, with a backbone/core Ocean observing capability, overarching governance and institutional arrangements, and roles and functions for nations and the EU;
- **Recommendation 2:** Empower and support streamlined, efficient coordination efforts such as EOOS and GOOS (including National Focal Points) to support Ocean observing activities at pan-European and global scales, thereby improving the overall efficiency of national and European investments in a shared *in situ* Ocean observation infrastructure;
- **Recommendation 3:** Strengthen the integrated combined capability of the Ocean observing system to deliver fit-for-purpose data and information supporting sustainable development, the 'Green Deal' and sustainable blue economy through connecting its funders, implementers and users;
- **Recommendation 4:** Establish an ongoing process to review the costs and performance of the system and map its economic and environmental benefits. At present, the collective benefits of sustained Ocean observations are often indirect and not always measurable, leading to poor and incomplete cost-benefit analyses. A continuous census of the results and products obtained from *in situ* Ocean observations with European, national and regional funding, would benefit management applications and prove useful to users such as industry, civil society, research and forecasting systems;
- **Recommendation 5:** Establish partnerships with the private sector (e.g. shipping, exploration and commercial industries) and civil society (e.g. philanthropic and other foundations, divers, boaters, citizen science) to enable the inclusion of wider Ocean observations and establish incentives to share those observations with a wide user base and support the marginal costs of using existing public and privately-owned infrastructures as Ocean observing platforms; and
- **Recommendation 6:** Co-design a holistic observing system that integrates all *in situ* observing capabilities with satellite observations and models. This will require well-functioning Ocean observation simulation capability (akin to a Digital Twin Ocean) that covers the value chain from data collection to applications and services and includes the cost and benefits of observations.

[54] https://www.mercator-ocean.fr/en/digital-twin-ocean/

The Ocean once thought to be 'too big to fail' and then 'too big to fix' is now recognized as 'too big to ignore' (Lubchenco & Gaines, 2019). It can no longer be 'out of sight and out of mind'. If the Ocean is to be integrated into the 'Internet of Things' then there will need to be a continuous presence of 'Things' in the Ocean.

Machine learning bias happens when computers adopt and amplify the human biases and prejudices locked into the data they consume. Without sustained observations sensing the subsurface Ocean, we are about to go into the digital age where decisions will be machine assisted by imposing our deeply engrained human 'out of sight, out of mind' bias about the Ocean beneath the waves. Rightly, considerable attention is now being given at the highest political levels to actions and solutions to reverse the cycle of degradation of the Ocean's health and productive capacity. But 'you cannot manage what you cannot measure' and timely Ocean information rooted in systematic sustained *in situ* Ocean observations will be integral to the design and evaluation of those actions and solutions. The impact of the COVID-19 pandemic[55] has proven that now is the time to accompany action with equal resolve to invest in a coherent, sustained way in an Ocean observation system that will provide the information needed to guide us on the path to the Ocean we want.

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