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Executive summary

The present work addresses the need for a more integrated approach in ocean observing in order to achieve truly integrated global and regional ocean observing systems. This work is a contribution to the implementation of the European Ocean Observing System (EOOS), a much-needed step forward in Europe, following the international guidance of the Global Ocean Observing System (GOOS).

As explained in **sections 1 and 2**, integration is a multi-faceted and multi-dimensional effort. It designates the process of efficiently collaborating among all the actors of ocean observing in order to optimally combine, across scales and disciplines, *in-situ* and remote observations and numerical models, exploiting the complementarities among different types of data, to produce an observing system that is more relevant than the sum of its individual contributions. An integrated approach thus requires strong and efficient coordination between observing networks, between modellers and observers, and between disciplines and areas of expertise, to ensure that all these elements are finely tuned to each other and constitute a coherent whole.

Although this process is the very foundation of the scientific approach, and therefore naturally occurs in scientific projects that concentrate on understanding specific ocean processes, this integrated approach has not yet been fully realised at larger scale and on an operational basis. Despite significant advances over the last two decades in more cooperation across the ocean observing activities, the ocean observing system still suffers from organisational silos, each network, team or nation establishing their own priorities and direction without substantial interaction with others. This lack of coordination has been a rising concern for the last 20 years, since it is a strong impediment to getting a more accurate and holistic picture of the ocean environment, thereby preventing ocean science from advancing at a faster rate. Moreover, the ambition of the United Nations Decade of Ocean Science for Sustainable Development (2021–2030) and the various efforts to grow a sustainable ocean economy and effective ocean protection efforts all require a more integrated approach to ocean observing. During the last two decades, there has thus been a rising awareness that enhanced integration is necessary to deliver more complete, consistent and sustained observations globally and better address the new and emerging scientific challenges.

Based on an intensive literature review and a careful examination of different examples of integration in different fields (**section 3**), it appears that integration is a very complex challenge that goes far beyond the traditional scientific and technological perspective. In all the examples examined, integration is more a matter of organisation and human interactions than technical issues. The lack of integration is generally due to a lack of common vision, a lack of leadership, too much emphasis on short-term results, a lack of clarity regarding the goals of integration, difficulties in communications, rigid vertical structures that create organisational silos, and overly individually-focused evaluation processes that lead to destructive competition between individuals or departments. Solutions to foster integration involve agreeing on a common goal, clearly defining roles and responsibilities among participants, focusing on long-term objectives, redesigning the organisational structure to foster more transversal approaches, and building an organisational governance framework that enables the establishment of a structured collaborative process.

Building on these results, **section 4** analyses the barriers that currently prevent the ocean observing system from becoming fully integrated. These barriers are summarised in four key points: (1) the norms and practices of the scientific system that tend to prioritise progress in narrow specialised fields and have led to the

development of an ocean observing system that is very much divided by disciplines and technologies, each one pushing to enhance its own capacities; (2) the lack of clear leadership and robust ocean observing governance structure for coordinating the end-to-end value chain, despite the coordination efforts exerted by GOOS and its regional alliances; (3) the limited resources available and the over-reliance on short-term *ad hoc* funding, which prevents the system to establish a common long-term vision and makes disciplines, technologies, networks and institutions compete against each other for funds, reinforcing the silos; (4) the research assessment system that create strong and sometimes destructive competition across disciplines and among scientists, and the insufficient incentives to participate in the coordination process in our science culture.

Achieving a truly integrated ocean observing system therefore requires fundamental changes in all these different aspects, which is not a simple task, since it implies moving beyond a business-as-usual approach, with a major shift at the cultural, behavioural, organisational, and management levels. **In section 5**, we suggest ten recommendations in order to initiate this transformative change. These recommendations include: (1) reforming the incentive system of ocean science, (2) agreeing on a common agenda and principles, (3) redesigning a polycentric ocean governance framework, (4) elaborating sustainable funding mechanisms, (5) developing new form of work organisation and management, (6) connecting the diverse communities, (7) establishing clear design and implementation plan, (8) facilitate the transition from research to operations, (9) building a coordinated data management system, and (10) efficiently communicating the value of ocean observing. We consider that all these recommendations are complementary and necessary, and the order of the items does not reflect priority ranking. However, the first five points are certainly among the most important since they would lay the foundation upon which this ocean integration could be built and from which the other points could naturally derive. They should therefore be the main priority.

Section 6 provides an overview of the very interesting feedback we received when presenting this work at different conferences. This evolution in the organisation of how we have been working so far in oceanography will not be easy, and will only be possible if scientists, institutions and funders embrace this change and collectively reflect on how to implement it. This work contributes to raising awareness on the importance of the cultural, behavioural, organisational and management aspects that need to be rethought for the achievement of a truly integrated ocean observing system. These recommendations aim at being a first step opening the way toward more reflection.

Finally, in **section 7**, we describe how this transformation could be achieved. To design and implement these changes, we envision a 5-to-10-year project that will continue this work and will: (1) lead a collective process of reflection and discussion on how to implement these changes, involving a wide variety of different stakeholders, including the major players of ocean observing as well as Early-Career Ocean Professionals (ECOPs) and experts from outside ocean science, and (2) implement these changes at multiple levels and scales in order to adapt to local conditions (one size never fits all!), potentially starting with some selected pilot regions, to be later extended to the other regions of the world.

1. Introduction

Science is built up of facts, as a house is with stones.
But a collection of facts is no more a science than a heap of stones is a house.
Poincaré (1901).

1.1. The ocean: a complex system that needs integration

The ocean is a complex dynamic environment with a strong interplay of physical, geochemical and biological phenomena at multiple and nested spatiotemporal scales. To obtain a comprehensive view of the system, an integrated approach is thus essential to combine a wide range of multidisciplinary data at multiple spatiotemporal scales. Moreover, it is impossible to simultaneously observe every aspect of the ocean. *In-situ* platforms (buoys, moorings, gliders, etc.) only observe the ocean at the position at which they are located, while remote platforms (HF Radars, satellites) only provide information at the sea surface. In addition, today we are capable of measuring only a limited number of ocean properties. In order to generate an overall understanding of the ocean, and predict its future variations, we thus need to optimally combine multiple *in-situ* and remote platforms together with numerical models to yield a consistent complementary ensemble of data at the appropriate scales. This requires strong and efficient coordination between observing networks, between modellers and observers, and between disciplines and areas of expertise, in order to ensure that all these elements are finely tuned to each other and constitute a coherent whole.

However, although this process is the very foundation of the scientific approach, and therefore naturally occurs in scientific projects that concentrate on understanding specific ocean processes, the same is not really occurring at larger scale and on an operational basis. The historical development of oceanography has created a highly fragmented patchwork of regional, national, public and private organisations that collect data and run models for their own purposes and are not used to collaborating between themselves. Although a coordination effort is exerted by the Global Ocean Observing System (GOOS) and its regional alliances, and despite significant advances over the last two decades in more cooperation across the ocean observing activities (e.g., Lindstrom et al., 2012; Moltmann et al., 2019), the ocean observing systems still tend to work in silos, each network, team or nation establishing their own priorities and direction without substantial interaction with others (EOOS Conference 2018 report and Call to Action, Larkin et al. 2018). As a result, the existing observing programs and networks tend to be focused on specific scientific or societal needs and are not well integrated with other observing systems, even in the same geographical area (Tanhua et al. 2019a).

1.2. Why is a change needed now?

Today, our society has to face a multitude of challenges related to the ocean: climate change, sea level rise, eutrophication, chemical contamination, marine litter, etc. To tackle these problems, there has been a rising societal and political demand for ocean data in order to inform decisions and support tracking of progress, ensuring that all aspects are considered. However, the existing observing programs are considered only partly adequate for addressing the new and emerging scientific issues. Specifically, they do not allow to get a holistic understanding of the ocean state and variability at different scales, in particular at the meso and submesoscale, where the ocean kinetic energy is maximum (e.g. Fox-Kemper et al. 2019) and where the impact on marine ecosystems and society is major (e.g. Levy et al. 2018). There are gaps in ocean observing coverage, with some important processes insufficiently measured, limiting our ability to precisely quantify some relevant mechanisms and interacting scales related to societal challenges, such as climate change (IPCC, 2019 Special Report on the Ocean and Cryosphere in a Changing Climate). Moreover, the sparsity of ocean observations and the lack of internationally agreed data standards makes implementation of data assimilation, data science and model verification frameworks difficult (National Academies of Sciences, Engineering, and Medicine, 2017; Davidson et al., 2019), which prevents the science of ocean prediction from advancing at a faster rate. In addition, today's challenges cannot be solved by one discipline alone. More collaboration and interactions between disciplines is thus needed.

During the last two decades, there has thus been a rising awareness that enhanced integration is necessary to deliver more complete, consistent and sustained observations globally and better address the new and emerging scientific challenges [e.g., National Research Council, 2011; International Oceanographic Commission (IOC)-UNESCO, 2017, 2020; European Marine Board, 2019; OceanObs'19, 2019; Tanhua et al., 2019a]. As stated in the EurOCEAN 2010 Ostend Declaration[1], "*Addressing the Seas and Oceans Grand Challenge requires the development of a truly integrated and sustainable European Ocean Observing System*". More recently, there has been an international trend toward more open science, more open data infrastructures, and a more concerted effort to conduct mission-oriented research (Mazzucato, 2018), and to translate science into services for society (e.g., World Meteorological Organization (WMO) reform of 2019[2]; United Nations Decade of Ocean Science for Sustainable Development 2021–2030, hereafter referred to as the UN Ocean Decade). We have therefore reached the point where it is urgent to promote better integration among all the components of the ocean observing system to ensure an optimal and efficient response to the priorities of international science and society needs. As called for by Lubchenco and Rapley (2020), "*It is time for strategic, collective action to change the culture of academia and create the enabling conditions for science to serve society better.*"

In addition, the lack of coordination among all ocean observing actors leads to inefficient planning and insufficient sharing. As stated in the 2019 Ocean Observation European Commission Consultation Inception Impact Assessment[3], "*ocean observations are made for a specific purpose, by a specific science community, and although these observations may also interest other communities and be used for other purposes, these communities have no say on where, when, and how these observations are made"*. Consequently, far too often observational data do not meet key requirements and cannot be used to their full extent. For example, of the large volume of *in-situ* data collected, only a limited portion is actually directly suitable for satellite calibration/validation activities, either because the measurements are not directly comparable, or because the observation is not properly located or provided with enough accuracy, or because the data are not accessible (Sterckx et al., 2020). Similarly, a large number of *in-situ* observations are not assimilated into numerical models due to insufficient spatiotemporal coverage (National Academies of Sciences, Engineering, and Medicine, 2017), or because the data are not provided with enough details about their quality, accuracy and precision. A better optimisation of the planning and design of ocean observations is thus needed in order to produce data that are fit for multiple purposes and reduce the duplication of efforts (e.g. European Marine Board, 2013, 20211; OceanOPS Strategic Plan, 2020). Furthermore, *in-situ* observing platforms are expensive tools that are not carbon neutral. An optimum design of these observing platforms is thus essential in order to maximise the benefits of these observations and reduce the ocean observing carbon footprint.

[1] https://www.marineboard.eu/sites/marineboard.eu/files/public/publication/EurOCEAN%202010%20and%20Ostend%20Declaration-76.pdf

[2] https://public.wmo.int/en/governance-reform

[3] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12539-Ocean-observation-sharing-responsibility_en

1.3. Purpose of this work

The present work addresses the need for a more integrated approach in ocean observing to achieve truly integrated global and regional ocean observing systems. The vision of this work is a worldwide ocean observing system that brings together all partners, for their mutual best interest and the great benefit of working together, to avoid duplication of effort and create an added value of working together. The goal is to jointly plan and design the activities in order to fully exploit the complementarities among *in situ* and remote observations and numerical models, with the aim to understand and predict the ocean state and variability across all scales, disciplines, and themes, and suitably addressing society needs. This ocean observing system is envisioned as a self-organized polycentric organization, in which many interdependent observing systems at local, regional and national scales interact with each other and are capable of mutual adjustment under an overarching set of rules.

Based on an intensive literature review and a careful examination of different examples of integration in different fields (section 3), this work identifies the issues and barriers that must be addressed (section 4), and proposes a vision for a real implementation of this ocean integration ambition. The final recommendations (section 5) are the result of a collaboration of 40 scientists from 30 research institutions from 20 countries over Europe, North America and Australia. These recommendations have been published in the peer-reviewed journal Frontiers in Marine Science under the title "*Ocean Integration: The Needs and Challenges of Effective Coordination Within the Ocean Observing System*." (Révelard et al. 2022). Part of the text of this report is taken from this publication. However, this report describes in more details the different examples of integration explored and the process that has led us to these conclusions. In doing so, we aim to give the reader a more detailed explanation of the different concepts and elements that have formed our understanding of how integration can be established and nurtured.

2. Ocean integration: what is it?

2.1. A multi-faceted and multi-dimensional concept

Ocean integration is a multi-faceted and multi-dimensional effort. It designates the process of efficiently collaborating among all the actors of ocean observing in order to optimally combine, across scales and disciplines, *in-situ* and remote observations and numerical models, exploiting the complementarities among different types of data, to produce an observing system that is more relevant than the sum of its individual contributions. This integration is also referred to as "organisational integration", which is defined as "*the extent to which distinct and interdependent organisational components constitute a unified whole, rapidly and adequately responding and adapting to each other while pursuing common organisational goals*" (Barki and Pinsonneault, 2005; Ricciardi et al., 2018).

In this work, the term "ocean observing" refers to the whole value chain, from the initial stakeholder/societal/scientific engagement that identifies the requirements for observations and establishes the design of multi-platform observations to the process of collecting/calibrating/validating data to the creation and delivery of products and services, often through data assimilation in numerical models. Ocean observing therefore includes the modelling and ocean prediction communities.

The value chain is a concept adopted from economics which allows to organise a system (in this case "ocean observing") into subsystems, each adding value with inputs, transformation procedures, and outputs, in a continual and iterative process (Figure 1; Bahurel et al., 2010; Garçon et al., 2019; Pinardi et al., 2019). *In-situ* and remote ocean observations and data delivery are at the basis of this value chain, and should therefore be designed and coordinated with all the stakeholder communities that exploit these observations to develop fit-for-purpose quality data, ocean prediction outputs and products and services, all of which benefit both science and society. The stakeholders include the engineering, technology, satellite, modelling, operational, weather, climate, and service delivery communities. Ocean integration therefore involves strong and efficient coordination between observing networks, between *in-situ* and remote sensing, between modellers and observers, between disciplines and domains of expertise, and between researchers, institutions and nations.

Based on this value chain approach, we can say that ocean integration has two components: the vertical integration, and the horizontal integration, as illustrated in Figure 1.

The vertical integration occurs along the value chain. It coordinates operations over the different stages of a single data/product using only one single platform (buoy, satellite, glider etc.). The goal is to ensure that the final data/product is fit-for-purpose, i.e. has been adequately processed and quality controlled to be distributed and to appropriately respond to at least one scientific/societal need.

Horizontal integration occurs at the same value level. It coordinates the activities between partners who work at the same level in the value chain in order to work toward a common goal and reach *a system-level focus rather than a sum of network approach* (JCOMMOPS Review, 2018). The goal is to create synergies between partners in order to elaborate products and services that integrate various data from various disciplines and platforms, resolving multiple spatiotemporal scales, and that are fit-for-multiple purposes, i.e. responding to multiple science and societal needs.

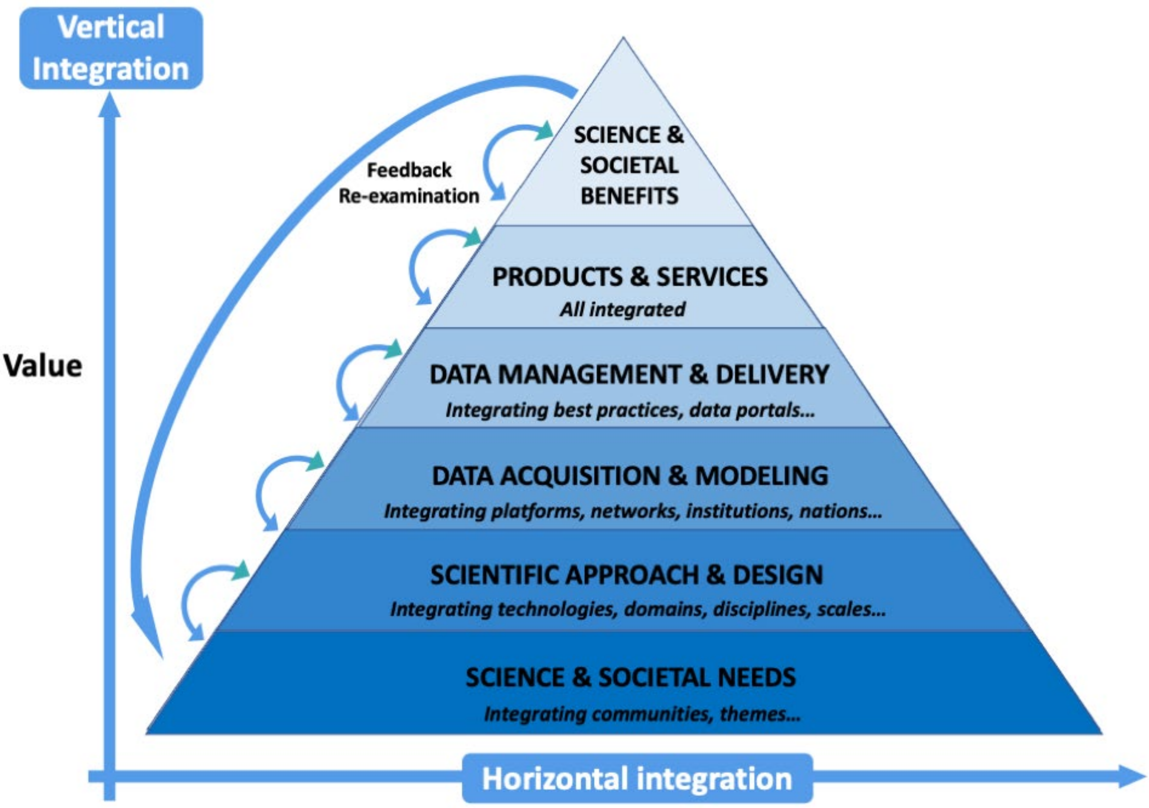

Figure 1. Illustration of the Ocean Integration concept showing the different components, horizontal and vertical. Vertical integration occurs along the value chain, while horizontal integration occurs at the same value level. Adapted from Pearlman et al. (2019) and European Marine Board (2021).

2.2. Integration ≠ uniformization. Diversity is key!

Integration does not mean uniformization. Integration means working together aiming at converging efforts towards a common goal, but this should not be achieved at the expense of diversity. Indeed, there are still major gaps in our understanding of ocean processes that prevent our capacity to resolve critical human needs. Basic process studies are therefore strongly needed to understand the relevant interacting scales, and diversity is an asset and an important factor in the advancement of knowledge, which also emerges from the creativity of scientists who let their research process run wild. The big challenge is therefore to implement integration without constraining diversity and creativity. Integration should contribute to interconnecting the large variety of individual knowledge in order to fit together and advance toward a complete understanding of the ocean environment. As stated by ESA in their Knowledge Management Initiative "*Our individual knowledge is like a piece of a jigsaw puzzle: it is fundamental, but it only works if joined with other pieces to fit together and have a complete understanding of the picture. By putting together our knowledge, we can do great things.*"[4] And the innovative spillovers that might result along the way may advance our knowledge of ocean science in an unforeseen way. For example, most of the technologies in our smart products today — from the Internet to GPS — emerged as spillovers from other research focuses of the past (Mazzucato, 2013, 2018). In the same way, in oceanography, there are several examples of advances in ocean knowledge that unexpectedly arose from other research focus (altimetry with the mean sea level rise, for example). A more integrated approach can therefore result in an innovation spillover that may have many unforeseen positive benefits on ocean science.

2.3. Some varying examples of integration in oceanography and related disciplines

As seen in the definition, ocean integration is a very holistic concept. The notion encompasses a wide range of different aspects (collaboration, cooperation, coordination, co-design, etc.), and a wide range of different dimensions that should be integrated (disciplines, scales, platforms, networks, themes, domains, stakeholders etc.). Therefore, there are at present no examples of fully integrated ocean observing systems that appropriately integrate all these aspects and dimensions. The past and current integration efforts generally focus on one or more dimensions, but not all. There are thus varying levels of integration, and we provide here some examples. This list of examples does not pretend to be exhaustive, but is only meant to illustrate the many forms that an integrated approach may take.

As said in the introduction, the best examples of integrated approach are the major science-based international programs or process studies, well focused on a specific scientific problem, where multi-platform and model integration is carried out during specific experiments. Other very good examples of integration are the majority of case studies, in which all relevant data available in the study region are used and combined for a specific purpose. However, these programs, projects or case studies are generally designed for advancing in the understanding of specific ocean processes, or for responding to one specific stakeholder's need, and therefore do not necessarily integrate all the dimensions cited above, beyond the immediate scientific/stakeholder interest. Examples of such approaches can be found in Annex 1 and 2, (section 10.1

[4] https://ideas.esa.int/servlet/hype/IMT?documentTableId=45087625531035594&userAction=Browse&templateName=&documentId=1355b822559eaa009275bf70f75ff984

and 10.2), where multi-platform observations and models are used for (section 10.1) model skill assessment for Search and Rescue operations and (section 10.2) the study of the effects of circulation on fish larvae.

Another example of integration can be the major data portals, such as the Copernicus Marine Service, EMODnet, SeaDataNet, etc., sometimes referred to as *integrators*. However, data portals only provide an integrated view of all ocean data available, but do not necessarily ensure that the planning and design of these observations have been done in an integrated manner. Yet, the development of integrated data portals and their associated dashboards in which all the metadata of the existing measurement systems in an area can be visualised can be a first step towards identifying additional measurement needs and integration opportunities to build an optimised observatory. An example of such approach can be found in Annex 3 (section 10.3), in which AZTI (Marine Research Institute located in the Basque Country, SE Bay of Biscay) describes the dashboard, topics, and the strategic actions ongoing towards the creation of a Super Observatory in the SE Bay of Biscay.

Another good example of integration can be the Global Ocean Data Assimilation Experiment (GODAE) whose aim was to demonstrate the feasibility and utility of real-time global ocean forecasting (Smith and Lefebvre, 1997; Bell et al., 2009). In order to complement satellite observations, the international Argo program was developed as a joint venture between GODAE and CLIVAR (Le Traon, 2013), and the integrated approach merging *in-situ* Argo observations with satellite altimetry and numerical models allowed to establish the state and variability of the large-scale open ocean circulation. This example is a good illustration of ocean integration as it optimally combines multiple observing platforms and numerical models to deliver a final useful product that provides relevant information on an ocean phenomenon. However, it only focuses on the large-scale physical processes and does not provide a holistic view of the oceanic system. This approach has been at the heart of the development of operational oceanography and of the present European Copernicus Marine Service (Le Traon et al., 2017), which provides a very good example of integration of *in-situ* and remote observations into numerical models (i.e. data assimilation) for the development of merged products made widely available to a wide range of users.

Another example of integration is the worldwide satellite altimetry community. It is a good example of integration because it brings together a wide range of expertise and combines multiple observations and data processing methods to obtain and publicly disseminate the final gridded sea level product (International Altimetry Team, 2021). Moreover, it needs to combine multiple along-track satellite data to obtain good space-time sampling and coverage.

Essential Ocean Variables (EOVs) and Essential Climate Variables (ECVs) can also be considered as an example of integration, as they shift the discussion from the need to have X number of platforms Y, to the need to observe an EOV at a determined accuracy and spatiotemporal coverage, possibly using many observing networks. The EOVs are thus independent of the observational platform, and have helped guide the ocean observing systems toward better integration across observing networks.

A striking example of the benefit of a well-focused integrated approach has been seen in the development of the glider platform. Gliders are an example of disruptive innovation and the innovation lies in the integration of all the components into an affordable, controllable, persistent mobile platform. Thanks to the well-coordinated work of scientist, engineer and Science and Technology Investor, who worked towards a common goal for a sustained period of more than 10 years, the incubation time has been half that of the usual instrument incubation time in oceanography (Curtin and Belcher, 2008). As concluded by Curtin and Blecher (2008), "*(...) a recipe for efficient, radical innovation is to work in collaborative, multidisciplinary* *teams, be tenacious and focused on long-term objectives while producing short-term successes, and find creative champions among funding agencies and investor organisations*".

Finally, outside the field of oceanography, meteorology also offers a good example of an integrated system, in which the various space-based and surface-based observing systems complement each other. It is a society-driven integrated system, based on societal requirements, focused on ensuring that the provision and delivery of meteorological and other environmental services respond to societal needs (Pinardi et al., 2019; World Meteorological Organisation, 2019). A wide range of users from all economic sectors and from all levels of government are actually routinely making decisions with very significant consequences entirely based on weather forecast, climate and hydrological outlook information (WIGOS vision for 2040). As the demand for meteorological and related environmental information from the user community (both public and private sectors and citizens) are continually evolving, the meteorological observing system has to adapt to the evolution of user requirements (greenhouse gas concentrations, ozone, carbon cycle, air pollution, water management, climate change, etc.).

3. The barriers and solutions to integration: examples from different fields

3.1. Integration in scientific research

This section analyses the barriers to integration in scientific research. Since the majority of ocean observing activities are carried out by research projects, this section is particularly useful for analysing the barriers that currently prevent integration in the current ocean observing system (section 4). Moreover, since for many aspects the state of ocean science is not yet sufficiently advanced to adequately respond to current societal needs, a more integrated and transdisciplinary approach in ocean science is also needed in order to address the current complex problems that are beyond the reach of traditional science. This is why this section is also very relevant for a discussion on how to foster more transdisciplinary research in ocean science.

3.1.1. Integrative science = inter- or transdisciplinarity

Integrative science is defined as a cumulative approach of scientific study that synthesises the perspectives of the individual disciplines, and integrates them during all phases of the approach to a question or problem, with the results having an influence on policy and management decisions (Gallagher et. al. 2008). In scientific research, integration thus generally refers to the process of combining multiple disciplines together, with the aim to address a specific societal need. An important concept that provides a good understanding of the varying degrees of integration is the difference between multi-, inter-, and trans-disciplinarity. These terms are often used interchangeably, as if there could be synonyms, but actually do have specific definitions. According to the literature, we can differentiate five step typology for describing the work within and across disciplines, each step requiring increasing integration and modification of the disciplinary contribution (Stember, 1991, see Figure 2):

- **Intradisciplinary**: working within a single discipline.
- **Crossdisciplinary**: viewing one discipline from the perspective of another.
- **Multidisciplinary**: people from different disciplines working together, each drawing on their disciplinary knowledge.
- **Interdisciplinary**: integrating knowledge and methods from different disciplines, using a real synthesis of approaches.

* **Transdisciplinary**: creating a unity of intellectual frameworks beyond the disciplinary perspectives.

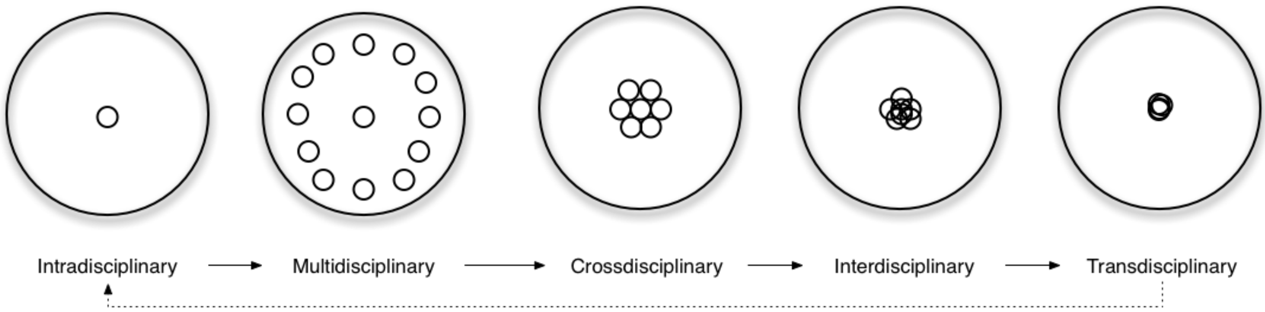

Figure 2. 'Sketch of the different disciplinarities' by Alexander Refsum Jensenius [5]

In 2006, Choi & Pak (2006) illustrated the difference between multi-, inter-, and trans-disciplinarity as mathematical equations, and then as food:

Table 1. Difference between multi-, inter- and trans-disciplinary, from Choi & Pak (2006) and based on a work from this page: makinggood.design/icmit.

	Multidisciplinary	**Interdisciplinary**	**Transdisciplinary**
Keyword	Additive	Interactive	Holistic
Mathematical example	2+2=4	2+2=5	2+2=yellow
Food example	a salad bowl (you can still see the individual ingredients)	a fondue or stew (melting pot) (ingredients are partially distinguishable)	a cake (the output is entirely different to the individual ingredients)

According to these definitions, transdisciplinary research is therefore the highest level of integration possible, in which different disciplines work together to produce a new, novel form or way of working that goes beyond the boundaries of the initial domains of expertise.

A slightly different accepted way of distinguishing inter- and transdisciplinarity is given by Tress et al. (2007):

* **Interdisciplinarity**: involving several unrelated academic disciplines in a way that forces them to cross subject boundaries to create new knowledge and achieve a common research goal
* **Transdisciplinarity**: involving academic researchers from different unrelated disciplines as well as non-academic participants, such as land managers, user groups and the general public, to create new knowledge and theory and delve into a common question.

According to these second definitions, transdisciplinarity thus combines interdisciplinarity with a participatory approach (Tress et al. 2007).

[5] http://www.arj.no/2012/03/12/disciplinarities-2/

3.1.2. The barriers to inter- and transdisciplinary science

In recent years, there has been an increasing emphasis on the importance of inter- and transdisciplinary research, but also a recognition that this isn't always easy to undertake effectively, or to support (e.g. Wildson et al. 2015). Indeed, integrative science requires to transcend the well-established silos of expertise, which is not a simple task, since it often implies a new way of working, with major shifts in philosophy within disciplines (Newhouse and Spring 2010).

According to Tress et al. (2006), the greatest barriers to integrative science are (see Figure 3):

- **Interpersonal & organisational barriers:**
    - Difficulties in communication because of the specialised language used by experts and a lack of common terminology;
    - Lack of clarity regarding the goals of integration and/or diverging project objectives between participants – often integration is recognised as desirable, but there is no clear understanding of what such integration would look like;
    - Lack of ownership in the project's integration phase – each participant may be interested in cooperation, but see it as someone else's job to coordinate the integration process and tell what they need to do to make integration happen.
    - Conflicts arising from the physical distance between team members, separating project participants;
    - The difficulty of agreeing on a common problem formulation

- **Time demands & external barriers:**
    - The considerable time demands of integrative research
    - The lack of necessary resources to conduct the project;
    - The fact that participants tend to start in projects at different points in time

- **Academic traditions & epistemological barriers:**
    - The difficulty of coping with different academic traditions
    - Varying frames of reference and assumptions across academic traditions leading to limited trust in other knowledge domains;
    - The academic merit system

This last point is indeed very important, as there is an important literature that denounces the fact that discipline-led metrics unfairly disadvantage inter- and transdisciplinary research (e.g. Rafols et al., 2011; Wilsdon et al, 2015; Hicks et al., 2015; Stirling, 2014; Benedictus and Miedema, 2016; Van Noorden, 2018; Nature editorial, 2018; Bleasdale, 2019; Coriat, 2019; Moher et al., 2020; OECD report, 2020, Lubchenco and Rapley, 2020; Hernández-Aguilera et al., 2021; Delgado-López-Cózar, 2021). This is because research metrics tend to prioritise progress in narrow specialised fields. As stated by Stirling (2014), "*Metrics for research evaluation tend to reinforce the power of traditional academic disciplines. Higher status journals in any field are typically those adhering most closely to central orthodoxies. Prized citation counts are most readily enhanced by concentrating work within a narrow disciplinary tradition*".

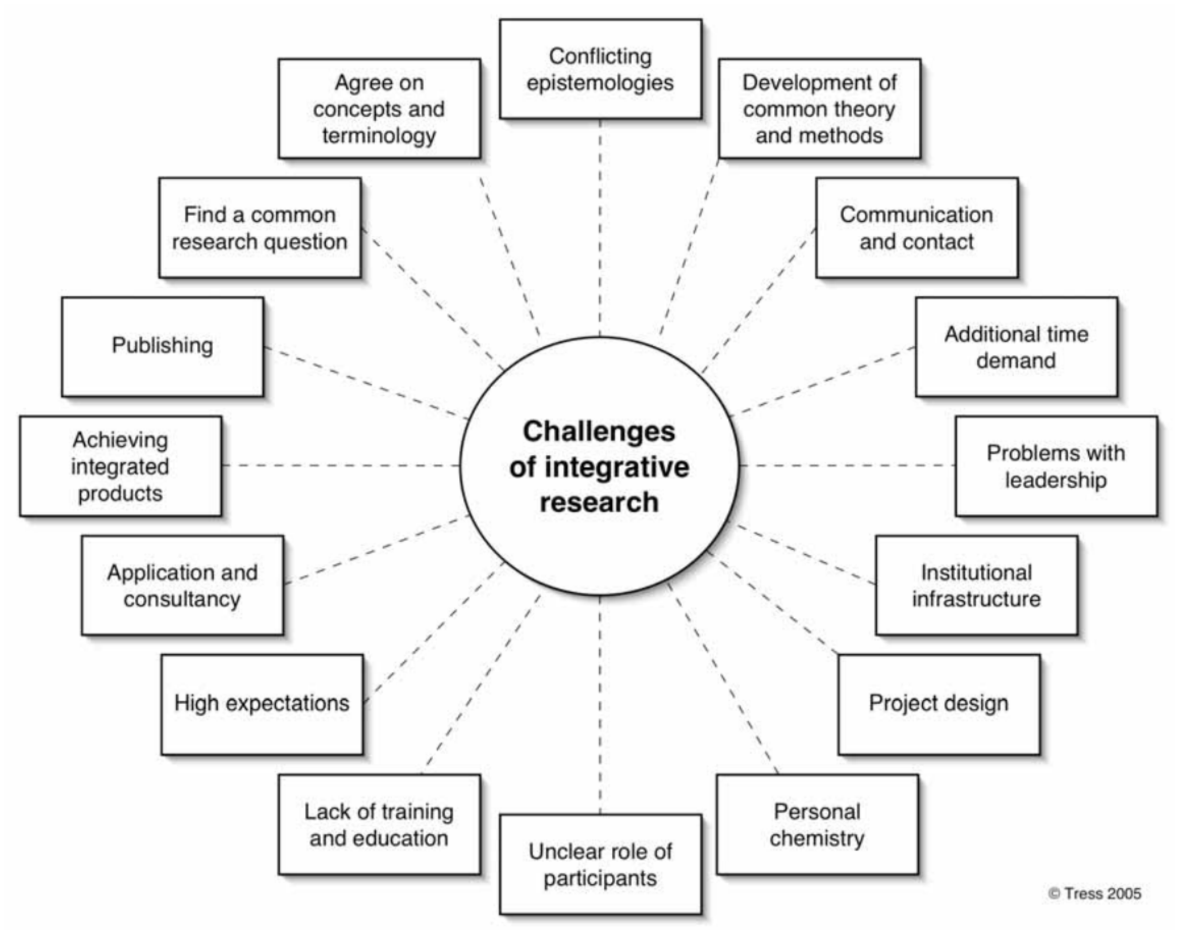

Figure 3. Overview of the challenges of integrative research projects, from Tress et al. (2006).

The other problem is that the current research assessment system encourages quantity over quality, and therefore there is a shift towards more mainstream, less risky research (Wilsdon et al. 2015). Moreover, inter- and transdisciplinary research requires a huge effort of communication and interactions with people outside our field, while the research assessment system does not properly value coordination and communication efforts.

In 2020, the Organisation for Economic Co-operation and Development (OECD) published a report entitled "*Addressing societal challenges using transdisciplinary research*" (OECD, 2020). This report identifies the key obstacles to effectively implementing transdisciplinary research. It states that many of these obstacles are embedded in the traditional disciplinary structures, norms and practices of our science systems but are amenable to judicious policy intervention. From this report: "*(...) despite increasing interest at the policy level, there are significant barriers to conducting rigorous TransDisciplinary Research (TDR). Science systems, their institutions, structures and processes, have been largely designed around distinct research disciplines and this presents a number of significant barriers to the promotion of TDR. Academic and professional training is normally organised in disciplines and not easily adapted to accommodate students who wish to engage in TDR. Peer-review, evaluation and promotion processes are likewise normally organised in disciplines and the key performance measures are based on scientific publications and citations, rather than societal benefits that are the main aim of TDR. Funding allocation mechanisms are mainly targeted at research excellence,* *which again is largely assessed in terms of scientific publication outputs. Excellence and rigour are equally important for TDR but there is a need to redefine how we evaluate and measure these qualities.*"

3.1.3. The solutions to foster inter- and transdisciplinary science

The OECD report recommends that governments, research agencies, research institutions and international bodies all take matters in hand to design and implement effective policy initiatives and foster more transdisciplinary research. In particular:

- **The governments** have a critical role to play in establishing the overall framework that enables and supports effective TDR. This includes: (1) providing dedicated and sustainable resources for TDR, (2) facilitating and supporting the engagement of public sector actors in TDR activities, (3) incentivising other actors, including from the private sector, to support and participate in TDR, and (4) promoting cooperation across ministries and responsible public authorities.
- **Research funding agencies** have a critical role to play by directly supporting and incentivising TDR research. This affects both prioritisation of research areas and changes to funding processes, including funding criteria, peer review and evaluation.
- **Universities and Public Research Institutions (PRIs)** are the principal organisations through which TDR is carried out and their long-term strategic commitment and support is essential. This has implications for education and training, as well as research. It also cuts across the so-called 3rd mission activities (societal engagement and innovation) of universities and PRIs.
- **The academic community** has a major influence on science policy development and the definition of research strategies and priorities. It is responsible for conducting peer review and evaluation processes and often has a strong voice in how these are designed and conducted. Key actions that can be taken by the academic community include: (1) the development and recognition of new inter- and transdisciplinary research fields, including the promotion of relevant scientific journals, (2) the participation in new research management approaches, including innovative peer review and evaluation processes and the development of new indicators and measures that would promote TDR, and (3) the development of international frameworks or programmes for TDR.

At the project level, Tress et al. (2006) analysed the "*Ten steps to success in integrative research projects*". According to them, integration does not come automatically in a project and should therefore be seen as an integral part of the work that needs to be part of the ethos and the organisation from the beginning. In particular, it often happens that everyone is convinced that integration is necessary but sees it as someone else's job, so providing resources and agreeing responsibility to coordinate the integration process is highly necessary. Moreover, integration is often recognised as desirable, but there is no clear understanding of what such integration would look like. It is therefore crucial to find agreement on a definition of the integrative concept. In addition, real and effective integration can be time-demanding (much more than we generally imagine), so a realistic assessment of needs, methods, time required and priorities for this coordination work is essential. Tress et al. (2006) recommend developing an Integration Implementation Plan that should be agreed by all participants. As integration is a creative process, this plan may certainly need adaptations and refinement throughout a project process, but remain an important guidance towards success. The selection of participants, appointment of a project leader and creation of an atmosphere of trust and respect are also, to a large degree, setting the course for the further project development.

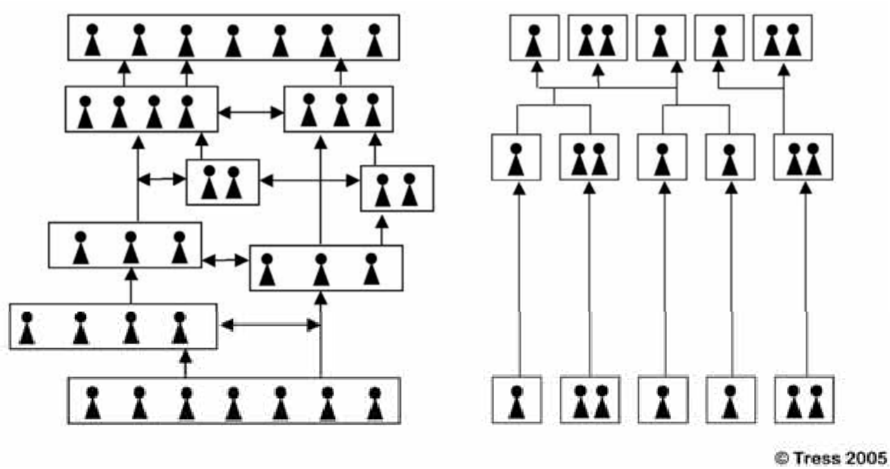

Figure 4. Integrative (left) and parallel (right) project designs, from Tress et al. (2006).

Moreover, the authors state that when designing an integrative project, a project group should choose an organisational structure that is able to foster integration. They suggest setting up the project with an integrative project design, and avoiding a parallel project design (Figure 4). "*In an integrative project design, the project teams start working together on a common goal from the beginning. In contrast, the parallel project design involves disciplinary subprojects that run parallel to each other without interaction until late in the project process. Participants try to integrate results in the end, when all disciplinary subprojects have delivered their results. However, this is the phase when most projects run out of time and money and integration proves to be impossible due to incompatibility of the different types of data and knowledge resulting from the disciplinary subprojects*".

3.2. Integration in business companies

In business, the lack of collaboration and integration between business departments or units is also a recurrent problem. Organisational silos in business terms is defined as the separation of different types of employees, often defined by the department in which they work. As described by Cromity and de Stricker (2011), "*the history of the term "silo" comes from "agricultural silos" which were trenches dug in the 1800s in Europe to create spaces for ensilage, corn and green fodder during cold winters. Silo is now a common term used to describe the fact that departments within organisations are isolated from each other and have few means of communicating. These silos create real barriers and limit broader, more collaborative opportunities for different teams to work together in different ways. Within any given organisation, institution, or business, a silo of knowledge can be a person, a department, an application, a database, or a network that only one or a few people can access*".

There is a lot of literature on the web about business culture and organisational silos, which all provide the same analysis. According to a Lighter Capital article series on the subject[6][7], silos are created within a company primarily due to a lack of clearly defined goals for the company, and a lack of communication of those goals throughout the company, allowing individual departments or groups to 'find their own way' of doing things. They are also created when there is a lack of urgency to obtain any particular corporate goal, giving group

[6] https://www.lightercapital.com/blog/what-are-organizational-silos/
[7] https://www.lightercapital.com/blog/causes-of-organizational-silos/

leaders the time to focus "inward on their kingdoms". "*It is usually a failure of leadership that allows silos to form and exist. (...) Organisational silos form when leaders, and ultimately employees, are allowed to develop more loyalty to a specific group or team than to the employer or company as a whole*".

According to Lighter Capital, organisational silos are due to:

- **Lack of team mentality:** lack of understanding as to how a particular department or team fits into the bigger picture.
- **Competition for resources:** if teams are forced to compete for resources, executives are only focused on the needs of their team, not the company.
- **Lack of communication:** each department is left to set their own priorities and direction without knowing or caring much about what the other departments want or need.
- **Losing focus of company goals:** when the overall company goals are not clearly spelled out, agreed to at the executive level and communicated to the rest of the company, teams are left to create their own goals.
- **Misguided incentives:** if different teams are incentivized in ways that can actually conflict with the success of the company.

These problems are so common that a wide literature is available on the web for providing advice on how to break down silos in the workplace. Commonly agreed recommendations are:

- **Define a single qualitative goal:** a company should clearly define its corporate goal, and this goal has to be measurable, time-based, and widely communicated throughout the company.
- **Have strong leadership:** regardless of the kind of management in the company (top-down or bottom-up, see next section), strong leadership is needed in order to pull people together and build a common vision for the company.
- **Remove internal competitiveness:** revise the way teams are incentivized for their work in order to be sure that these are not counterproductive and make teams fight with one another.
- **Redesign the organisational structure:** consider changing the departmentalization structure of the company in order to divide teams in a different way and allow for a better alignment between teams and the purpose of the company.

It is interesting to see that very similar conclusions are reached both in the context of inter- and transdisciplinary research and in the context of business companies. As we can see, in both cases, integration is more a matter of organisation and human interactions than technical issues. As stated by Cromity and de Stricker (2011), "*It's not the Technology, it's the Culture!*". According to them, the main barriers to integration are:

- **Behavioural barriers:** those associated with attitudes, motives, age, environment, and culture. They come from desires of individuals and their reaction to changes, and in particular their difficulty in changing organisational culture working habits.

- **Multi-generational barriers:** age spreads present significant challenges and barriers to businesses as they encounter practicalities pertaining to values and work habits.

As stated by Coakes et al. (2009), "*if knowledge sharing doesn't already occur, technology is unlikely to help*".

3.3. Integration for managing the world's natural resources

For decades, our planet's natural resources have been the subject of intense research on how to best manage them and ensure that they are used responsibly, effectively, equitably and sustainably. This has led to the development of initiatives providing a frame for promoting the integrated development and management of these resources. As explained by Diedrich et al. (2011), "*in order to address sustainability challenges in the last decade, the scientific community has dedicated increasing attention to the need to consider human social systems and ecological systems as one, often referred to as social-ecological systems. This perspective is reflected in new Integrated Management (IM) approaches to addressing sustainability challenges that seek to combine scientific research and information with management processes and policy development".*

In the context of resource management, integration thus refers to the idea of considering the system as a whole (the social-ecological system), and to the fact that multiple factors and stakeholders need to be taken into account for decision making processes. Examples of this approach include, among others, the Integrated water resources management (IWRM), the Integrated Forest Management (IFM), the Integrated Coastal Zone Management (ICZM) and the Marine Spatial Planning (MSP).

The same can be applied to the ocean. In his report about the economy of the sea[8], Miguel Marques claims that only an integrated approach to the oceans can ensure they are used responsibly, effectively, and equitably, guaranteeing a proper balance between all those who have a stake in it (governments, academia, businesses, individuals, environment), taking into account the differing and sometimes conflicting needs of each of them. According to him, there are 2 significant challenges in achieving an integrated approach:

1. Understand that the timescales at sea are longer than the new digital world is happy to tolerate.
2. Lack of awareness about the scale of the opportunity, which in turn means that investment in this area is seen as a low priority.

According to M. Marques, 3 essential elements are required to put an integrated approach into action:

1. **The right framework**: a governance foundation, ensuring there is clarity on the different rights and responsibilities of those operating on the seas, and a shared commitment to standards of safety and security. To ensure adequate protection, minimise bureaucracy, and give greater confidence to investors, especially in emerging industries.
2. **The right people**: training people. The new economy of the sea demands – and creates – jobs with much higher levels of skill, from engineers to scientists to information technologists.
3. **The right technology and equipment**: highly specialised equipment.

The first point (i.e. the need for a solid governance foundation) is indeed one of the major concerns for achieving an integrated management of our world's natural resources. As explained by Serra-Llobet et al. (2016) in the context of water management, "*while there is widespread acknowledgement that no single governance approach is effective in all contexts, researchers have sought to define broad principles for the design of integrated and adaptive water governance, which emphasise multi-level structures, collaborative*

[8] https://www.pwc.com/gr/en/industries/pwc-helm-world-2020.pdf

decision-making, and broad stakeholder participation. These findings are by no means conclusive, and many questions still remain. In particular, there is debate over the scale at which such governance should be organised, and whether authority for different aspects of water management should be centralised, or distributed across multiple actors."

Over the different governance mechanisms that exist, two clearly distinct management approaches can be highlighted: the "top-down" management approach, and the "bottom-up" or "community-based" management approach.

The "top-down" management approach involves having a single centralised authority responsible for implementation. This centralised authority thus generally has strong leadership. One of the advantages of this management method is that it sets clear goals and expectations, as goals are delivered by one authority, and the message is not diluted by multiple voices. Moreover, it is sometimes easier for central authorities to promote participation, resolve conflicts, and set common standards. Another advantage is that there is generally a good alignment with international priorities, as this central authority is usually closely connected to international frameworks. However, this management approach also has strong disadvantages. Since the rules are generally imposed in a dictatorial way, without consultation with the local communities to ensure these rules fit the local context, the rules decided are not necessarily congruent with local conditions. Moreover, as resource users are not engaged in the process, they have no say in how the rules of sacrifice are made, and are thus less likely to abide by them (Ostrom, 2009).

The "bottom-up" or "community-based" management approach, on the other hand, refers to governance in which multiple governmental and non-governmental entities (such as individual resource users) agree to collaboratively decide upon a common set of goals and implementation strategies. To achieve this, they usually agree on rules, moral and ethical standards (Ostrom, 2009). These arrangements are often viewed as more conducive to learning due to dialogue occurring across multiple parties, a critical feature for adaptive management (e.g. Serra-Llobet et al., 2016).

One of the strongest advocates of this approach has been Elinor Ostrom, the first woman to be awarded the Nobel Prize for economics in 2009 for her work on the commons. Elinor Ostrom refuted the assumption that the shared use of natural resources was bound to lead to a "tragedy of the commons", whereby competition for their use inevitably led to overexploitation (Bauer and Dombrowsky, 2012). By aggregating research from different disciplines (political economy, economy, political science, but also ecology, hydrology, anthropology, geography, legal theory and many others who had looked at the commons too) and analysing several case studies on commons that were effectively managed, Elinor Ostrom demonstrated that common resources can be effectively managed collectively, without government or private control. More generally, Elinor Ostrom's research demonstrated that cooperation is possible. She showed that humans have a more complex motivational structure and more capability to solve social dilemmas than posited in earlier rational-choice theory (Wall, 2017).

The analysis of numerous case studies enabled Elinor Ostrom to come up with **eight design rules** which were based on similarities she found from looking at the various long-lasting commons (Wall, 2017):

1. **Clear defined boundaries:** Commons can't be free-for-all or open to all passers-by.
2. **Rules fitted to local circumstances:** the rules for commons use had to fit local circumstances (committee establishing precise rules over a whole country or region would fail, although regional and national decision making can also be needed in some cases).

3. **Self-governance:** Individuals who use the commons need to be able to participate in the making and modifying of rules.
4. **Effective monitoring**: need to record any infractions of the rules and put in place people to do it
5. **Graduated sanctions**: Punishment is needed, but it has to be carefully graded.
6. **Low-cost conflict resolution**: differences in the interpretation of the rules can be mediated by an agreed judicial body, even if it is highly informal.
7. **Recognition of the rights of the commoners**. Control from above or paternalistic regulation from external authorities can be damaging because it is insensitive to local conditions.
8. **Common is part of a wider enterprise**: a local irrigation system run as a commons is part of a wider water network. Unless local commons can work with other systems, failure will be likely.

It is now generally accepted that a balance is needed between "bottom-up" (i.e., collaborative and participatory) governance, and centralised "top-down" control (Huntjens et al. 2012; Pahl-Wostl, 2009; Serra-Llobet et al. 2016), in order to take the benefits of both approaches. As stated by Gayner et al. (2014) in the context of Marine Protected Areas (MPAs), "*Community-based MPAs have been shown to be long-lasting and more likely to attain compliance, similar to other community-based resource management. Community-based initiatives occur more commonly with smaller coastal MPAs (e.g. fisheries closures, no-take areas near communities, or Locally Managed Marine Areas), where the community of users lives in close proximity to the protected area and consequently experience direct impacts and benefits. On the other hand, centralised or top-down management can also be effective, especially in achieving broader (e.g. regional) biodiversity conservation objectives through the establishment of larger open ocean MPAs*." However, they also add that "*Both top-down and bottom-up approaches have been criticised for failures to meet conservation objectives and sustain engagement of stakeholders over time*."

3.4. Integration for large-scale social change: collective impact organisations

One type of organisational framework that has been increasingly popular in the last decade and that in some way combines the top-down and the bottom-up approaches is the collective impact organisation. Collective impact organisations have been highlighted by Kania and Kramer (2011), by analysing several successful collective impact initiatives in the United States that have led to large-scale social change thanks to a cross-sector collaborative framework. According to them, "*A collective impact is reached when a core group of community leaders decide to abandon their individual agendas in favour of a collective approach for solving a specific social problem. It is when all these leaders realise that fixing one point in the system continuum wouldn't make much difference unless all parts of the continuum improve at the same time. Thus, no single organisation, however innovative or powerful, could accomplish this alone. Instead, the ambitious mission is to coordinate improvements at every stage of the system. It is not about creating a new system or attempting to convince funders to spend more money. Instead, it is about focusing the entire system on a single set of goals, measured in the same way, through a carefully structured process. It is about developing shared performance indicators, discussing their progress, and most importantly, learning from each other and aligning the efforts to support each other.*"

Based on the analysis of several successful case studies, they came up with the Five Conditions of Collective Success (Kania and Kramer, 2011):

1. **A common agenda**

"*Collective impact requires all participants to have a shared vision for change, one that includes a common understanding of the problem and a joint approach to solving it through agreed upon actions. (...) Each organisation often has a slightly different definition of the problem and the ultimate goal. These differences are easily ignored when organisations work independently on isolated initiatives, yet these differences splinter the efforts and undermine the impact of the field as a whole. Collective impact requires that these differences be discussed and resolved. Every participant need not agree with every other participant on all dimensions of the problem. In fact, disagreements continue to divide participants in all of our examples of collective impact. All participants must agree, however, on the primary goals for the collective impact initiative as a whole (...)*".

2. **Shared Measurement Systems**

"Developing a shared measurement system is essential to collective impact. Agreement on a common agenda is illusory without agreement on the ways success will be measured and reported. Collecting data and measuring results consistently on a short list of indicators at the community level and across all participating organisations not only ensures that all efforts remain aligned, it also enables the participants to hold each other accountable and learn from each other's successes and failures. (...) Each type of activity requires a different set of measures, but all organisations engaged in the same type of activity report on the same measures. Looking at results across multiple organisations enables the participants to spot patterns, find solutions, and implement them rapidly. (...)"

3. **Mutually Reinforcing Activities**

"Collective impact initiatives depend on a diverse group of stakeholders working together, not by requiring that all participants do the same thing, but by encouraging each participant to undertake the specific set of activities at which it excels in a way that supports and is coordinated with the actions of others. The power of collective action comes (...) from the coordination of their differentiated activities through a mutually reinforcing plan of action. (...) [Leaders] *do not prescribe what practises each of the 300 participating organisations should pursue. Each organisation and network is free to chart its own course consistent with the common agenda, and informed by the shared measurement of results."*

4. **Continuous Communication**

"Developing trust among nonprofits, corporations, and government agencies is a monumental challenge. Participants need several years of regular meetings to build up enough experience with each other to recognize and appreciate the common motivation behind their different efforts. They need time to see that their own interests will be treated fairly, and that decisions will be made on the basis of objective evidence and the best possible solution to the problem, not to favour the priorities of one organisation over another. Even the process of creating a common vocabulary takes time, and it is an essential prerequisite to developing shared measurement systems. (...)"

5. **Backbone Support Organisations**

"Creating and managing collective impact requires a separate organisation and staff with a very specific set of skills to serve as the backbone for the entire initiative. Coordination takes time, and none of the participating organisations has any to spare. The expectation that collaboration can occur without a supporting infrastructure is one of the most frequent reasons why it fails. The backbone organisation requires a dedicated staff separate from the participating organisations who can plan, manage, and support the initiative through ongoing facilitation, technology and communications support, data collection and

reporting, and handling the myriad logistical and administrative details needed for the initiative to function smoothly. (...)"

Finally, one of the critical points for success is **the appropriate funding**. As stated by Kania and Kramer (2011), "*Creating a successful collective impact initiative requires a significant financial investment: the time participating organisations must dedicate to the work, the development and monitoring of shared measurement systems, and the staff of the backbone organisation needed to lead and support the initiative's ongoing work. (...) Collective impact requires (...) that funders support a long-term process of social change without identifying any particular solution in advance. They must be willing to let grantees steer the work and have the patience to stay with an initiative for years, recognizing that social change can come from the gradual improvement of an entire system over time, not just from a single breakthrough by an individual organisation. This requires a fundamental change in how funders see their role, from funding organisations to leading a long-term process of social change."*

In the context of ocean observing, this collective impact organisation model has been put forward for helping maintain sustained ocean observations and expand funding opportunities (National Academies of Sciences, Engineering, and Medicine, 2017, 2020; Weller et al., 2019). It has been argued that, while the ocean observing system should be primarily a federal responsibility, the collective impact organisation framework could be a model that could be drawn upon to create an efficient Ocean Partnership across all the different sectors involved in ocean observing (government, academia, private sector, nonprofits and philanthropic organisations). As we will see in the next sections, this collective impact organisation framework could indeed be a relevant model for building a robust ocean observing governance structure and foster an integrated approach among all actors of ocean observing.

4. Ocean Integration: the barriers and challenges ahead

In this section, we analyse the barriers and challenges that prevent integration within the basin-wide and regional ocean observing systems in Europe and beyond, such as AtlantOS in the Atlantic (deYoung et al., 2019), TPOS in the Tropical Pacific (Smith et al., 2019), IndOOS in the Indian Ocean (Beal et al., 2019), IMOS in Australia, IOOS (and its Regional Coastal Ocean Observing Systems) in the U.S., EuroGOOS or MonGOOS in Europe, among others. In the last decades, these regional systems have made substantial advancement in the process of integrating multi-platform and multi-disciplinary data and modelling for the creation of value-added products. However, as seen in the previous section, integration must build upon well-defined and common goals, so that all partners work together collaboratively toward a shared purpose and vision. Yet, the historical development of ocean observing and the way the ocean observing systems are organised and managed have led to the development of strong systemic barriers that are hindering these systems from becoming truly integrated.

4.1. A research-based system

Although government agencies, private sector companies and resource users also collect and accumulate quite a large amount of data for their own purpose, the majority of national and regional agencies responsible for funding and running *in-situ* ocean observing systems are research-based, rather than operational. Most of the ocean observing systems are thus led by a bottom-up science-based approach, and driven by scientific objectives such as discovery, understanding and excellence. In many cases, observing systems are conducted by independent research teams through often disconnected research-funded projects. These projects are primarily designed for advancing in the discovery and understanding of ocean processes, and therefore do not necessarily contribute to the development of data that are directly relevant to societal needs. At local to regional scales, *in-situ* observations are mostly led by individual scientists working to establish themselves as principal investigators as part of their career ladder. The framework of these projects is driven by research agendas, and thus suffers in areas such as integration, sustainability and sharing, beyond the immediate interest. Local and regional environmental consultants also collect and accumulate quite a large amount of data for their reports, in many cases responding to requests from public entities. However, such data may not be at all findable or quality-checked or trusted. To implement integration, we rely on the goodwill of the various actors in creating harmonious and effective coordination and fostering open science.

At a global level, there has been considerable progress by the GOOS Observations Coordination Group in the capabilities and in the integration across the value chain of the individual observing networks (Argo, OceanSITES, SVP drifters, OceanGliders, HFRadar, etc.). Significant coordination has been established in areas such as metrics, standards and best practices, with the elaboration of the FAIR (Findable, Accessible, Interoperable, Re-usable) Data Principles (Wilkinson et al., 2016; Tanhua et al., 2019b) and the establishment of the Ocean Best Practices System (OBPS, Pearlman et al., 2019). Considerable progress has also been made by GOOS toward enhanced collaboration among national systems, regional alliances, global networks, and *in-situ* observing and remote sensing (Moltmann et al., 2019). All this has contributed in making substantial advancement in the process of integrating multi-platform and multi-disciplinary data and modelling for the creation of value-added products.

However, despite this progress, there are still many areas where more coordination is needed. As detailed in deYoung et al. (2019), issues remain that are hindering these systems from becoming fully integrated, such as the insufficient collaboration between the observing networks and systems, and the too-narrow focus of the existing observational networks. In many cases, each network, team or nation establishes their own priorities and direction without substantial interaction with others (EOOS Conference 2018 report and Call to Action, Larkin et al., 2019 Ocean Observation European Commission Consultation Inception Impact Assessment[9]). As a result, the existing networks tend to be focused on specific scientific and/or societal needs and do not yet fully exploit their complementarities, even in the same geographical area (Tanhua et al., 2019a).

4.2. The lack of governance structure

Contrary to the satellite altimetry and the meteorological systems (given as examples of integration in section 2.3) which benefits from a strong leadership and a well-defined governance system, the other barrier to integration in ocean observing is the lack of clear governance structure. In the case of satellite altimetry, a clear governance structure with a few key players was established, mostly led initially by research agencies, NASA, CNES, and ESA, and now extended to the Committee on Earth Observations Satellites (CEOS) and operational agencies (NOAA, Eumetsat). In the case of meteorology, WMO is a strong centralised organisation where nations contribute based on a treaty, with clear mandates and legal obligations. In the much wider field of ocean observing, the governance structure is unclear and fragmented (IOC-UNESCO, 2017, 2020; Tanhua et al., 2019a; European Marine Board, 2021; Smith, 2021). A large variety of institutions and initiatives deal with ocean management and governance at local, regional, national and international levels (Valdés et al., 2017; Muñiz Piniella and Heymans, 2020). However, they often overlap geographically and/or in their mandates or subject agendas, with only marginal coordination between them. At national

[9] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12539-Ocean-observation-sharing-responsibility_en

level, responsibilities and financing for ocean observing activities are often distributed across multiple ministries and sectors, and unfortunately, formalised national coordination structures such as national focal points or national ocean committees are rare or dysfunctional (deYoung et al., 2019; Lara-Lopez et al., 2021; Smith, 2021). Internationally, ocean affairs are spread throughout a number of UN organisations (Valdés, 2017), with some leadership for ocean observing coming through GOOS and IOC-UNESCO. To integrate national systems into regional ones, thirteen GOOS Regional Alliances (GRAs) have been created, covering most regions of the globe. Yet there is significant heterogeneity in the governance, funding and data policies and indeed the performance of GRAs (Moltmann et al., 2019; Tanhua et al., 2019a). The present form of arrangement lacks resources, authority, clarity and transparency, which leads to confusion around roles, responsibilities, accountability, leadership, and cross-support system engagement and coordination (Smith, 2021).

4.3. The lack of reliable long-term funding

Another difference between meteorology and the ocean observing system is that public and political interest in weather forecasts has led to sustained funding, including private companies lobbying to maintain observing infrastructures (e.g., Spiegler, 2007; Weller et al., 2019; National Academies of Sciences, Engineering, and Medicine, 2020). In comparison, the global and regional-scale ocean observing systems mostly lack reliable sustained funding. Most *in-situ* observing networks are financed through research projects that are subject to 3– 5-year funding cycles, with no funds or time-budget allocated to cover the costs and the time needed for the coordination with other research projects. As seen in section 3.1, integration is very time-demanding and requires stability and long-term planning, which is difficult without appropriate resources and support structures. Sustained core funding associated with a centralised infrastructure greatly enhances integration, as seen for example in the U.S. Integrated Ocean Observing System (IOOS) and the Australian Integrated Marine Observing System (IMOS). In Europe, for more than 10 years, there have been discussions on how to improve ocean governance and create new innovative funding models to support the ocean observing system (and more specifically the *in-situ* system) as a public-good infrastructure (e.g., European Marine Board, 2013; Expert group on marine research infrastructures, European Commission, 2013). One possible solution currently envisioned is a European hub-and- spoke model, similar to IOOS and IMOS, with a centralised European backbone entity with subscription based or binding Nationally Determined Contributions, combined with national infrastructures (European Marine Board, 2021).

To support ocean observations, there has been a debate in the US on how to expand funding opportunities (National Academies of Sciences, Engineering, and Medicine, 2017, 2020; Weller et al., 2019). It has been argued that, while the ocean observing system should be primarily a federal responsibility, a new, flexible and nimble organisation engaging with non-profits organisations, philanthropic organisations, academia, government agencies, and the private sector could address some of the challenges in maintaining sustained observations. This organisation should be based on the principles of a collective impact organisation (Kania and Kramer, 2011), which gives a framework for organising a decentralised landscape of stakeholders interested in addressing a common complex issue. This governance model is similar to, and founded in, the polycentric multi-level governance promoted by Ostrom for managing the world's common resources (Ostrom, 2010), and could be a model that could be drawn upon to create an efficient ocean governance that would provide a sustained foundation for ocean integration. As detailed in section 3.4, a collective impact organisation involves establishing a common agenda, continuous communication, shared metrics, a backbone infrastructure with a dedicated staff, and mutually reinforcing activities among all participants.

This framework is similar to that of the Integrated Coastal Zone Management (ICZM, e.g., Cicin-Sain and Knecht, 1998; Diedrich et al., 2011, see section 3.3) and much could be learned from some of the solid advances in the implementation of ICZM guidelines worldwide (e.g., The Pegaso Project 2014).

4.4. The lack of incentives

The lack of collaboration among networks, institutions and scientists stems from insufficient incentives to participate in the coordination process in our science culture. Indeed, integration is a matter of long-term collective multi-dimensional efforts, which can be out of line with traditional career-advancement metrics. Research is currently assessed essentially through bibliometric indicators, making publication the primary objective of research, at the expense of the other aspects of the research mission such as delivering solutions to societal problems that are regarded as "unproductive" activities by scientists since these activities do not tangibly further their careers (e.g., Hicks et al., 2015; Wilsdon et al., 2015; Delgado-López-Cózar et al., 2021). Moreover, the evaluation process predominantly targets individual researchers or individual networks rather than teams, departments, or observing systems. This reinforces the silos and can have a distorting impact on integration, interdisciplinarity, information sharing and well-being more generally (e.g., Coriat, 2019; Moher et al., 2020). Given the societal expectations of ocean science in the context of the UN Ocean Decade, there should be concern about the misalignment between these expectations and the way scientists are evaluated for their work. Many of the skills required for effective collaboration, such as communication skills, community relationship building, and the open-mindedness to constructively debate, are undervalued in academia (e.g., Lubchenco and Rapley, 2020; Hernández- Aguilera et al., 2021). This acts as a disincentive for scientists contemplating participation in coordination activities, and threatens the continuity of the workforce to sustain ocean observing in the future (National Academies of Sciences, Engineering, and Medicine, 2017; Weller et al., 2019). Excellence and rigour are still one of the pillars in an integrated approach, but there is a need to also recognize and reward engagement with the community, communication, coordination and sharing, as well as the essential need to document data and observation/analysis methods (Pearlman et al., 2019). As Lubchenco said, "not all scientists will want to (or should!) engage, but all should value and support those who do" (Lubchenco, 2017).

This is in line with the general international trend toward the redefinition of scientific excellence (e.g., Benedictus and Miedema, 2016; Nature Editorial, 2018), which considers that research should be assessed in terms of multiple aspects rather than just on journal-based publication metrics (Raff, 2012; Leiden Manifesto, Hicks et al., 2015). The development of new indicators together with a more careful and reflective human review to ensure an appropriate translation and interpretation of indicators are regarded as strongly necessary. Change is progressively taking place: several European funding agencies are now adopting the use of narrative curricula vitae formats, and various institutional initiatives have proposed new evaluation models (e.g., University of Cambridge[10] and Exeter[11], UK; Macquarie University[12], Australia; Utrecht University[13], Netherlands ; see the blog, resources page, and case studies of the DORA website[14] for more examples). Dutch research institutes and funders have come up with a most notable initiative. They have announced the development of a new system of recognition and rewards, with equal emphasis on five key areas of education, research, impact on society, leadership and (for university medical centres) patient care,

[10] https://www.cam.ac.uk/research/news/cambridge- university- signs- san- francisco- declaration- on- research- assessment

[11] http://www.exeter.ac.uk/staff/exeteracademic/yourdevelopment/

[12] https://staff.mq.edu.au/work/development/academic- promotion/new- scheme

[13] https://www.uu.nl/en/research/open- science/tracks/recognition- and- rewards

[14] https://sfdora.org

as detailed in the position paper "Room for everyone's talent: toward a new balance in the recognition and rewards of academics" (VSNU et al., 2019). Considering that "it is unrealistic as well as unnecessary for each academic to excel in each of the key areas," they advocate for a greater diversity in competences and talents among academics. Among other things, bibliometric publication indicators will no longer be used and the inclusion of research output on curricula vitae and application forms will take on a more narrative form. At Utrecht university for example, the impact factor is formally abandoned and by early 2022 every department will judge its scholars by other standards, including their commitment to teamwork and their efforts to promote open science (Woolston, 2021).

5. Proposal for specific actions

We must learn how to dissect and harness complexity,
rather than eliminate it from such systems.
Ostrom (2009).

This ground-breaking advancement in the way Dutch academics are evaluated and rewarded is fully aligned with the spirit of the UN Ocean Decade, which aspires for real transformational change and encourages the scientific community to think beyond business as usual. To advance toward a more integrated approach in ocean science, we may likewise need to change the status quo and rethink some parts of our ocean science system. In the following subsections, we suggest ten recommendations focusing on those aspects that we consider as essential for initiating cultural, behavioural, organisational and management changes within the scientific community in order to reach a better organisational integration in ocean observing. We consider that all the proposed approaches are complementary and necessary, and the order of the items does not reflect priority ranking. However, the first five points (i.e., redefine scientific excellence, agree on a common agenda, redesig ocean governance, elaborate sustainable funding mechanisms and develop new forms of work organisation and management) are certainly among the most important since they would lay the foundation upon which this ocean integration could be built and from which the other points could naturally derive. They should therefore be the main priority.

5.1. Recommendation 1: reforming the incentive system of ocean science

Dealing with the multi-faceted challenges of integration requires a long-term vision and the interplay of a rich diversity of talents and skills. The incentive system of ocean science thus urgently needs to change in order to meet current needs and allow for greater diversity in possible career paths and profiles. Research assessment should focus more on long-term outcomes and on the overall ocean observing system benefits than on short-term results. The contribution to ocean observing systems and their implementation (including governance) should be highly valued, as well as the participation in coordination work. Sharing data and the methods for collecting or creating data is key to this integrated approach (more details in section 5.9). Gathering data and providing FAIR and open data in a timely manner, together with the methods and best practices used to collect or create the data (Pearlman et al., 2021), should therefore be properly recognized and rewarded (Hodson, 2018; Tanhua et al., 2019b). This would help to foster a cultural change toward more information sharing, encouraging scientists to make their data and methods FAIR and publicly available even before publication. Moreover, the long-term implication of data gathering needs to be considered. Finally, communication activities, training, education, and mentorship should also be duly recognized, as well as the compliance with the Responsible Research and Innovation (RRI) principles.[15]

In light of the growing worldwide trend toward reforming the research evaluation system aforementioned, and following the initiative of the Dutch research institutes and funders, a new system of recognition should be developed, with balanced emphasis on publications, coordination, contribution to the overall ocean observing system, impact on society, data gathering, data management and sharing, best practices development, communication, education, mentorship, training, leadership and team building, without constraining scientists to excel in all these areas. This would encourage the scientific community to be more deeply involved in coordination and integration tasks, and would ensure a greater recognition of the technical, engineering, communicative and collaborative aspects of the work that are indispensable for the achievement of ocean integration. It would also contribute to a more diverse, equal and inclusive ocean observing community and make the ocean science system a more coherent whole. A diverse set of metrics should be developed to quantify these accomplishments, and inappropriate indicators that create the wrong kind of incentives such as journal impact factors and citation counts should no longer be used, in favour of more comprehensive metrics and a more narrative- based assessment.

5.2. Recommendation 2: agreeing on a common agenda and principles

Building on the mission-oriented approach proposed by Mazzucato (2018) to address the global challenges of our time, on the principles of collective impact organisations described by Kania and Kramer (2011) and put forward by Weller et al. (2019), and on the principles of ICZM (e.g., EU ICZM Recommendation 2002/413/EC[16]), we suggest applying the same approach to establish a more mission-oriented and mutually supportive scientific community. To work collaboratively toward a shared vision, a common agenda that will define the missions on which to focus should be agreed. As explained by Mazzucato (2018), missions should be broad enough to engage the whole community, but focused enough in order to join forces toward clear goals. Missions do not specify how to achieve success, but stimulate the development of a wide range of different solutions to achieve the common goal. It is thus a powerful tool for establishing a clear direction while fostering bottom-up research and innovation solutions.[17] The ocean observing community has therefore everything to gain from addressing the Grand Challenges related to the ocean as missions. This will result in an innovation spillover that may have many unforeseen positive benefits on ocean science (Mazzucato, 2018).

To achieve this agenda, the ocean observing community should agree on fundamental principles that will serve as governing rules for reconciling divergent interests or perspectives and setting up a joint approach, similar to the above-mentioned principles on which ICZM is based. Those principles should define the primary objectives of the integrated approach, the various dimensions that need to be integrated (platforms, networks, regions, disciplines, modellers and observers etc.), the common agenda to which all members commit, the responsibility in which they engage, their respective central roles, and the ways progress will be measured and reported. These principles should determine the essential elements with standards of data

[15] https://www.rri- practice.eu/about- rri- practice/what- is- rri/

[16] 2002/413/EC, Recommendation of the European Parliament and of the Council of 30 May 2002 concerning the implementation of integrated coastal zone management, OJ L148 of 6.6.2002. http://data.europa.eu/eli/reco/2002/413/oj

[17] The Ocean-Shots concept from the US UN Decade initiative is an ambitious, transformational research concept that draws inspiration and expertise from multiple disciplines and fundamentally advances ocean science for sustainable development. https://www.nationalacademies.org/our- work/us- national- committee- on- ocean- science- for- sustainable- development- 2021- 2030

and measurements, and the requirements for an observing element to be considered as respecting the principles of integration. Regional components should be agreed in order to align global priorities with regional ones and create benefits at local, national and regional scales, but all regions should have a common baseline. As in collective impact organisations (section 3.4), those principles should serve as guidelines for all members to establish their own specific strategy and activities. Each organisation is free to chart its own course as long as it fits into the overarching plan and is coordinated with the actions of others. The success of organisational integration will come from the back-and-forth discussions between all members and from the coordination of mutually reinforcing activities.

5.3. Recommendation 3: redesigning a multi-level ocean governance framework

As stated by Tress et al. 2006 in the context of an integrative research project, integration does not happen automatically and should therefore be seen as a necessary part of the work that needs to be tackled from the beginning. Coordination takes time, so providing adequate financial and human resources and agreement on the responsibility to coordinate the integration process is essential. Such work requires a separate infrastructure with a dedicated staff with a very specific set of skills to serve as the backbone, just as in collective impact organisations. As indicated by Weller et al. (2019), this backbone infrastructure is not designed to impose things or to set the common agenda, but should be responsible for providing strategic high level intentions and organisational capabilities to coordinate the integration process and to plan, manage, carry out and support that agenda, based on the fundamental principles previously agreed by all members. As most ocean observations are funded at a national level, permanent national organisations such as ocean agencies, equivalent to the meteorological agencies, involving both scientists and funders and supported by a sound governance structure, should be set up to improve the communication between the various national observing systems, with significant savings in maintenance and operating costs. It would also enable countries to act more coherently at the international level, and improve the dialogue with policy makers and funding agencies. However, in some cases, regional organisations might be more efficient than national ones for harmonising and coordinating the ocean observing value chain at the regional scale. In Europe, EOOS could be designed as the backbone entity for harmonising and coordinating these national and regional organisations together with the European ones, with a coordination body funded with subscription-based or binding Nationally Determined Contributions, as proposed by the European Marine Board (2021).

At a global level, GOOS should act as the international backbone infrastructure providing authoritative guidance and supporting the decentralised landscape of ocean-related organisations worldwide, coordinating local, regional, national and basin-wide organisations to span all spatial scales and disciplines. To reach this goal, the GOOS infrastructure should be rejuvenated in order to develop the organisation's ability needed to meet these objectives. We therefore fully support the current work that is now being carried out within GOOS to reorganise its governance.[18] GOOS should have a dedicated staff, separate from the other ocean observing system organisations, who can plan, manage and support the integration process through ongoing facilitation, technology and communications support. There should be clarity and transparency about the respective responsibilities of GOOS, the regional organisations and the national ones, with clear connections between them. A GOOS funding model similar to the one proposed for EOOS, with binding contributions from national and regional entities, might perhaps reinforce their engagement with GOOS. Finally, as also recommended by Moltmann et al. (2019), the benefits of being part of GOOS need to be much more apparent to countries, institutions, programs and ocean observers. In addition to incentivizing

[18] GOOS 10th Steering Committee https://www.goosocean.org/index.php?option=_com_oe&task=viewDocumentRecord&docID=28265

researchers and facilities for their contribution to the overall ocean observing system (see section 5.1), there is also a strong need for GOOS to work on building leadership in order to become more attractive. Providing authoritative guidance and assistance for establishing the design and implementation of observing systems (see section 5.7), for helping the transition of observing systems from research to operational (see section 5.8), and for leading the interdisciplinarity process (see section 5.6) would certainly be elements contributing toward achieving this objective.

5.4. Recommendation 4: elaborating sustainable funding mechanisms

The ocean observing system should be considered as a public- good, and sustainable funding should support its long-term collective nature. The pressing issue of climate change - and the resulting increase in ocean-related hazards - and the necessity of developing a more sustainable ocean economy, make ocean observations and forecasts of increasing economic importance. However, the OOS is not receiving the financial resources appropriate to the issues at stake. The grand majority of ocean observation and prediction activities are funded on an ad hoc basis, mostly through research funding agencies. Because research funds are so scarce, and increasingly reduced, the OOS suffers significant capacity constraints, and is far from having the human and financial resources needed to meet current societal expectations. Given the economic importance of ocean observing (see section 5.10), public, private, and academic sectors could cooperate with mutual benefits, as is the case in meteorology with the Weather Enterprise (e.g., Spiegler, 2007). The ocean observing community could create an equivalent level of visibility, lobbying, and advocacy for funding, for example through initiatives such as the Benefits of Ocean Observations Catalog[19] drawn up by IOOS. However, to be convincing, the ocean observing community needs to be better organised to reach out to the public in a more coordinated and impactful manner. As Smith said, “support will begin to flow once the “house” is in order and is investible” (Smith, 2021). Moreover, a common agenda should be agreed so that the ocean observing community all align behind clear priorities for missions (see section 5.2). This would help to attract sustainable funding, for example from Member States subscriptions, as is the case for WMO. In addition, the financial needs should be quantified in order to provide concrete numbers on what is needed to support the system. There is currently no robust estimate of the cost and human capital of the ocean observing infrastructure needed, as this cost depends on the purpose and final design (Kite-Powell, 2009). This makes the discussion with policy makers and funders difficult (e.g., National Academies of Sciences, Engineering, and Medicine, 2020; European Marine Board, 2021). Designing how a fully integrated ocean observing system might look (see section 5.7) is therefore the first step for estimating the resources and time-budget required.

In addition, overheads need to be clearly estimated and funded. Although integration undoubtedly has a strong impact on the cost-effectiveness of the system, it requires a substantial financial base that is generally not supported by research- funded projects. New types of funders such as mission-based entities are therefore needed to help create and sustain the long-term collective process, recognizing that ocean integration will not come from a single breakthrough, but through the gradual alignment of all parts of the system. At a national level, there are already initiatives to fund more mission-oriented projects (i.e., Ocean-Shots in the US). Global and regional programs should therefore be in phase with such national initiatives. Finally, the role of the private sector needs also to be recognized, both as a provider of technologies and as a key intermediate user for the creation of services tailored to specific end-user needs. This is what is expected for the development of the “New Blue Economy” (Hotaling and Spinrad, 2021), with technology

[19] https://ioos.noaa.gov/ioos-in-action/benefits-of-ocean-observing-catalog/

providers, public agencies and public and private intermediaries delivering value-added information products and services to a wide range of end-users. The "Ocean Enterprise" commercial activity is already significant in scale and scope (NOAA, 2017, 2021; Rayner et al., 2019a), and a greater connectivity with the commercial players could strengthen the organisational and financial case for the ocean observing system.

5.5. Recommendation 5: developing new form of work organisation and management

Work organisation refers to how work is planned, organised and managed within institutions and to choices on a range of aspects such as department structures, work processes, job design, responsibilities, task allocation, work scheduling, work pace, rules and procedures, and decision-making processes[20]. Today it has been demonstrated that the most effective teams and the most competitive/successful companies put special emphasis on their organisational structures. They have established an innovation culture and improved their innovation capability. In ocean science, we also need an organisational innovative change. We need to develop new organisational structures in order to move from the conventional disciplinary or platform-oriented department structures to a new innovative functional organisation that is more conducive to integration. This means dividing teams in a different way to allow for a better alignment between teams and the high-level and long-term purpose of ocean observing systems. This does not mean to completely remove the functional departmentalisation, which divides teams in function of their expertise. This departmentalisation may still be relevant for some aspects. However, as recommended by the OECD for transdisciplinary research (OECD, 2020; see section 3.1), more integrated approaches (such as challenge-based or thematic-based approaches) should be introduced in research strategies and organisational structures. Moreover, sustainable institutional structures and mechanisms such as cross-department committees and meetings and shared infrastructure should be developed to foster cooperation across disciplines and technologies. Also, the establishment of structures and mechanisms to build long-term trusted relations with external stakeholder communities, including interfaces with civil society, private and public sector, should be a key element for the future.

Today, there also exist new modern and holistic approaches to organisational management that have proved to be more effective than traditional management for fostering innovation and facilitating exchange between departments and teams (Agile, Scrum, Holacracy, etc.). These new kinds of management are based on the belief that the traditional top-down, command-and-control approach to management is no longer effective in today's fast-paced, ever-changing work environment. Instead, modern management focuses on creating self-organising teams, empowering employees, promoting collaboration and knowledge-sharing, and creating a supportive work environment that fosters innovation and continuous improvement (e.g. Cowen et al. 2004). Today, organisations in wildly different contexts and competitive situations have firmly embraced these new modern forms of management (Di Fiore et al. 2019). It is only recently that institutions in academia are exploring how these modern management techniques popular in sectors outside academia could be implemented to boost scientific research (Di Fiore et al. 2019; Pirro 2019; Cristini et al. 2022). Much could be learned from these holistic management approaches in order to foster more coordination and collaboration within teams, institutions and networks.

5.6. Recommendation 6: connecting the diverse communities

Engagement with stakeholders to understand their needs and requirements is essential for an efficient design of the ocean observing value chain. The planning and design of an integrated ocean observing system will

[20] https://www.eurofound.europa.eu/topic/work-organisation

therefore need to be defined jointly with other scientific communities, such as the weather, the climate, the satellite, the modelling, the operational and the service delivery communities. For some dimensions (e.g., coastal ocean, ecosystem state, fisheries), the perspectives of local and indigenous communities as well as other coastal-ocean related disciplines should also be considered. This requires overcoming the silos between disciplines and going beyond conventional practices by including more diverse perspectives within the ocean observing community. For example, an increased intergenerational exchange by mixing early, mid- and late-career professionals could result in broader perspectives and more integrative approaches. At a higher level, closer collaboration is needed between the GOOS OCG, the GOOS discipline-based expert panels, the Expert Team on Operational Ocean Forecasting System (ETOOFS), the Joint WMO-IOC Collaborative Board, the CEOS working groups, as well as with other programs such as CLIVAR[21], OceanPredict[22], and CoastPredict[23]. For example, an internationally agreed organisation could help to coordinate communication between the different scientific disciplines at project conception.

5.7. Recommendation 7: establishing clear design and implementation plan

Agreeing on a common agenda entails agreeing on the objective we want to achieve. This means that we need to prioritise certain observations and collectively design how a fully integrated ocean observing system should look (as pursued by the AtlantOS (deYoung et al., 2019) and TPOS2020 (Smith et al., 2019) projects, among others), in accordance with the agreed agenda, and develop a long-term (5–10 years) implementation plan to put this system in place. This involves challenging ourselves to provide answers to practical questions, such as the exact number, location and the type of instruments and platforms that are the most appropriate to sufficiently resolve the specific spatiotemporal scales of a given ocean phenomenon. The GOOS driven effort to agree on Essential Ocean Variables is an example of this and shift the discussion from the need to have X number of platforms Y, to the need to observe an EOV at a determined accuracy and spatiotemporal coverage, possibly using many observing networks. The next step would therefore be to agree on Essential Ocean Phenomena and their corresponding observing configurations, and combine them to obtain the fully integrated observing design. Various spatial scales (global, basin, regional, coastal and local) need to be considered and integrated among themselves. For ocean prediction, this means identifying the observations that lead to improved forecasts (Davidson et al., 2019). Providing concrete numbers would not only ensure better communication with policy makers and funders, but would also provide useful guidance that will enable a more strategic approach to this investment. Moreover, once this implementation plan will be approved and funded, the competition for funds between the networks would be hindered.

This collective work requires the observing networks to be objective and look beyond their own interests, taking care to avoid network-specific approaches, as recommended by Moltmann et al. (2019). The multidisciplinary potential of each platform should be fully exploited in order to enhance the overall cost efficiency. This calls for trust and flexibility by all parties involved, and a willingness to reach the common goal. It is also key that the community be open to vigorous and regular re-examination of the ocean observing system elements to insure that the agreed objectives are being met. A kind of peer- review open process through a coordinating body is needed in order to assess the quality and overall efficiency of the system, which entails discussions with stakeholders. This requires a dynamic, agile process that could also retire old

[21] https://www.clivar.org

[22] https://oceanpredict.org

[23] https://www.coastpredict.org

networks that are not needed or not sufficiently cost-efficient. It could be the responsibility of GOOS, in collaboration with other experts, to establish this implementation plan and the evaluation process.

The involvement of the modelling community is key for several aspects, since it can identify which observations are needed to improve the models and reduce the biases and provide guidance on the optimal observing design using data assimilation tools (Davidson et al., 2019). In fact, Observing System Evaluation (OS-Eval) methods have been used for decades by space agencies and others to test different designs of new satellite systems prior to their launch, and help justify investments in new observing systems (Zeng et al., 2020). Due to the large systematic errors in ocean models, increased sophistication in OS-Eval methodologies is needed, as well as multi-system evaluations to improve the robustness of the results and reduce system-dependency (Fujii et al., 2019). This entails strong international coordination and enhanced communication between the modelling and observational communities in order to increase the reliability of those experiments and take full advantage of these techniques, as recommended by Fujii et al. (2019).

5.8. Recommendation 8: facilitating the transition from research to operational

The overall ocean observing system should be enhanced by upgrading and integrating existing research-based elements into a global integrated sustained operational framework. Observing systems must have certain characteristics in order to meet the criteria for operationality, sustainability, and integration. First, they must meet a user's needs (ideally multi-purposed), and be coordinated and complementary to other observing systems. Moreover, they must be sustainable and must provide data with the necessary metadata in a timely, cost-effective, and efficient method. These operational observing systems undoubtedly provide critical information for basic research but there is often a compromise between flexibility for the research question and meeting the criteria for integration, sustainability, and application to a broad range of users. There is therefore a strong need for facilitating these twin aspects and assisting the research teams in the transition from research to integrated sustained operations.

First, we need to set standards regarding the requirements for a research-based observing system to adapt and be accepted as part of the integrated sustained observing system. It should be the responsibility of a rejuvenated GOOS or the regional organisations to take up this responsibility and assist the transition. In developing countries, where this transition would be most difficult due to limited sources of public funding, GOOS could coordinate pools of donor funds to assist such transitions where it is needed the most, for example through the WMO Systematic Observations Financing Facility.[24] Second, research teams should be funded and incentivized for this work (see section 5.1). Third, new policies at regional and global level could be key elements to foster this transition. Finally, we need a shift in our ocean science culture. In the same way operational weather prediction centres contribute to research and also benefit from it, in oceanography the linkage between research and operational teams is mutually beneficial, and a close link between these communities is essential. Once scientists are incentivized for operational work, oceanographers could decide whether they prefer to work on research projects or be involved in sustained operational capabilities, in a similar way as weather measurements are sustained by operational entities, rather than aggregates of researchers.

5.9. Recommendation 9: building a coordinated data management system

Observational data are only usable if they are delivered with the appropriate accuracy and precision, and with enough details on their collection practices and provenance for the users to decide which data to use

[24] https://public.wmo.int/en/our- mandate/how- we- do- it/development- partnerships/Innovating- finance

for a specific purpose. Data should therefore be FAIR, but also timely distributed for feeding the operational ocean prediction systems (Davidson et al., 2019) and made freely available. The methods used to collect or create the data should also be open and available (Pearlman et al., 2021). Despite the great advances toward these objectives, partly through the activities of the IOC/UNESCO's International Oceanographic Data and Information Exchange (IODE), much progress still needs to be made. While the key elements for a good data management plan have been established (see e.g., Tanhua et al., 2019b) and for some teams and even regional organisations incorporated into their work routines [e.g., the Argo (Tanhua et al., 2019b) and the IMOS (Lara-Lopez et al., 2016) data management systems], there are still barriers to sharing, inherent to the culture and the organisation of our science system. On the one hand, the "publish or perish" culture found in the realm of scientific research makes many scientists possessive and protective of "their" data. As a result, researchers are often reluctant to share data prior to publication. On the other hand, scientists have few incentives to expend the effort necessary to make their data sets available, as standardising and disseminating data is costly (about 10–20% of the budget of oceanographic research projects, Brett et al., 2020) and time-demanding, but not rewarded and acknowledged to be of equal value to publishing scientific papers. Furthermore, government agencies and private companies such as those in oil and shipping also collect a large amount of data of their own purpose, but these data are not publicly shared, for fear of what they might reveal (brett et al. 2020). We therefore need to find ways to put all these elements in place and foster a systematic application of these principles among all the ocean observing community.

First, to avoid duplication and heterogeneity, a common data delivery approach must be adopted by all actors and all organisations involved in data acquisition and management. This requires strong coordination, so we need an international collaborative framework to implement this work at the different levels: national/regional research infrastructures, networks and clusters as well as at the international level. This framework should consolidate the work developed by research teams into best practices and should be agile enough to make the best practices evolve to follow the progress of research and to handle new platforms/sensors/variables implemented by researchers. The data integrators (such as SeaDataNet,[25] CMEMS,[26] or EMODnet[27] in Europe) should also be able to adapt to new observational data flows. This framework should include organisations dedicated to provide guidance and training for assisting the data management work of the data providers, since this work is time-demanding and can be beyond the technical reach of many science groups.

Second, following the FAIR and open access principles, developing best practices, and providing training to assist their implementation, should be rewarded and acknowledged to be of equal value to publishing scientific papers (see section 5.1). Many options exist in order to give credit to datasets through data citation tools, such as DOIs or Persistent Identifiers for Data (PIDs) and/or products (see Tanhua et al., 2019b for more details). Traceability of use tools using DOIs and PIDs should be implemented to provide feedback to the originators when the data are shared or used through a downstream product. Similarly, DOIs should be assigned to methods used in the value chain to provide recognition of scientists that create and document the practices used in their research. Moreover, a standardised approach is needed for the attribution and acknowledgment of funders. Incentivizing researchers and facilities to make their data FAIR and publicly available would help ensure that the data management work is contemplated and funded in all research

[25] https://www.seadatanet.org

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

[27] https://emodnet.eu/en

projects, whether the transition to accepted operational status is envisioned or not. The TPOS 2nd report[28] and Tanhua et al. (2019b) suggest 10% of the funding of science projects should be devoted to data management, and this is what IMOS dedicates to this activity from its core funds (Lara-Lopez et al., 2016). Finally, binding international regulations could also help guarantee that this data delivery approach is followed. The new unified WMO data policy[29] is a good example of a top-down measure that will encourage more data sharing. Considerable progress has been made in Europe with the INSPIRE directive,[30] but implementation is still insufficient.

5.10. Recommendation 10: efficiently communicating the value of ocean observing

In the same way meteorology and space observations are considered essential for all who live on earth, the general public and decision-makers should understand that ocean observing is also of primary importance for all the world's people, and especially for achieving the Sustainable Development Goals (SDGs) of the 2030 Agenda.[31] Ocean heat distribution controls the weather and climate and is crucial for forecasting natural or climate change-induced hazards. Ocean carbon absorption controls atmospheric CO2 accumulation and is a key element for establishing the carbon budget. Ocean currents are key for operational services, and ocean biodiversity and productivity impact fisheries and ocean health (e.g., National Academies of Sciences, Engineering, and Medicine, 2017). Consequently, many of the SDGs are related to the ocean. Moreover, although the benefit-cost ratio of ocean observations is difficult to estimate since it strongly depends on the cost of the observing system and on the economic importance of the user sectors (Kite-Powell, 2009), it is becoming clear that ocean observations support a wide range of societal and economic benefits (e.g., Rayner et al., 2019b). For IMOS for example, this benefit-cost ratio has been estimated to be in the range of 7.6–12 to 1 for the Australian government (Lateral Economics, 2021).

However, far too often the importance of ocean observations in the daily life of citizens and their nations is not communicated well, in part because we, as scientists, do not know how to efficiently communicate and provide answers to practical questions (National Academies of Sciences, Engineering, and Medicine, 2020). More effective and coordinated outreach efforts to communicate the value of ocean observing to broad audiences are therefore needed. The pressing issue of climate change and the increasing demand for a sustainable management of the ocean health and operational services is a suitable conduit for these efforts. Incentivizing researchers and facilities to communicate on the value of ocean observing (see section 5.1) will strongly contribute to enhancing the sharing and communication of science, and would encourage scientists to improve their communication skills and actively team with communication experts. Moreover, social scientists as well as professional communicators could also be engaged.

6. Feedback received when presenting these recommendations

All these recommendations (except recommendation 5 which have been added afterward), have been published in January 2022 in the peer-reviewed journal Frontiers in Marine Science under the title "*Ocean Integration: The Needs and Challenges of Effective Coordination Within the Ocean Observing System*." (Révelard et al. 2022). After publication, this work have been presented in four different conferences:

[28] https://tpos2020.org/project- reports/second- report/

[29] https://public.wmo.int/en/our-mandate/what-we-do/observations/Unified-WMO-Data-Policy-Resolution

[30] https://inspire.ec.europa.eu/inspire- directive/2

[31] https://sdgs.un.org/publications/transforming- our- world- 2030- agenda- sustainable- development- 17981

- May 2022: the EuroSea annual meeting, Cádiz, Spain
- June 2022: the OceanPredict/EuroSea workshop (online)
- October 2022: the Ocean Best Practices System workshop VI (online)
- November 2022: the north-western mediterranean workshop (VilleFranche sur mer, France)

Here we compile the different feedback we received during these conferences.

➔ Defining one common goal is very difficult and perhaps utopic. Another way to move forward would be to focus on "exemplar projects'' as defined by the Ocean Observing Co-design UN Decade Program. However, at the high strategic level, there is a strong need to align priorities between EU, national funders (member states), and the scientific community (institutions).

➔ To implement more transdisciplinary approaches, we need to transform the educational system. For example, there could be mandatory transdisciplinary courses at universities. Also, students should be trained in a more holistic manner, considering the whole aspects of ocean science, such as ecology, biology, physics, etc. Structural changes could also appear in the publishing industry (with the development of cross-cutting transversal sections).

➔ The lack of strong leadership, the lack of resources, and the impossibility to have long-term vision and planning are one of the principal difficulties for implementing a collective impact approach. To make organisational changes, we need a set of leaders to be convinced to make these changes (for example the major scientific institutions). Moreover, training researchers in modern management approaches, ethics, and coordination skills is crucial.

➔ The EU is an extremely complex landscape. There is a very strong need to develop EOOS as a backbone coordination structure, (with all components of the value chain?). National coordination is also crucial. In some countries, the ocean is governed by the ministry of traffic, or commerce. We need to create new structures with a committee, bringing all ocean-related stakeholders, e.g. national focal points such as "Ocean ministries". At the EU level, the problem is that DGs do not talk to each other so much. We need integration between DG MARE, DG Research and DG DEFIS.

➔ Need to differentiate between an operational system and research-based system. The observing system should not be decoupled from science, but basic research cannot be paying for the sustained operational ocean observing system. A perfect example of this is the meteorological system. Ocean observing could build upon the organisational system of meteorology. And for this, we need to efficiently communicate the value of ocean observing. Meteorology was driven by need, while oceanography was driven by curiosity. We need to remind society that oceanography also has a big value.

➔ There is a strong need to change the way we assess success and careers, and to develop new tools and indicators to measure collaboration impact. The reform of the research assessment system might indeed help to move towards a more "integrative culture", but this will not be sufficient.

➔ The difficulties identified for implementing transdisciplinary research (OECD report 2020, Tress et al. 2006, etc. see section 3.1) are indeed highly representative of the difficulties facing regional multidisciplinary ocean observing systems, especially the coastal observing systems, where coastal interactions require a wide range of disciplinary teams to operate.

- ➔ Scales: need to work on all scales. Regional, national and international at the same time.
- ➔ Might be interesting to build questionnaires to ask oceanographers about their needs and issues in their daily work.
- ➔ Now it is the moment to incorporate social scientists and lawyers into this challenge.
- ➔ Need for cultural change in order to make our organisation more agile and less afraid of change. For example, a new culture should be adopted where it is ok to fail.

7. Initials ideas for implementation

We are at a unique moment in time where we both have the scientific and technical capabilities as well as urgent societal and political drivers. The UN Decade of Ocean Science for Sustainable Development offers a once-in-a-lifetime opportunity to bring the global community together to design and implement the science needed to ensure a healthy and sustainable ocean. In particular, there are strong expectations for the development of digital twins of the ocean, which will critically depend on our capacity to work all together and combine all the different assets. To achieve its ten challenges, the UN Ocean Decade aspires for real transformational change and encourages the scientific community to think beyond business as usual. This offers a unique opportunity to rethink how the ocean observing system is conducted and build an innovative organisational framework that is more adapted to the challenges of our time.

This work allowed us to identify 10 dimensions in which initiatives should be undertaken to change the status quo and advance toward a more integrated ocean observing system. To design and implement these changes, we envision a 5-to-10-year project that will continue this work and will: (1) lead a collective process of reflection and discussion on how to implement these changes, involving a wide variety of different stakeholders, and (2) implement these changes at multiple levels and scales, potentially starting with some selected pilot regions, to be later extended to the other regions of the world.

Since this project aims to address a very complex challenge for which there are no easy, obvious, straightforward solutions, the project will begin by leading a collective process of reflection and discussion among a wide range of stakeholders, including the major players of the ocean observing system and key actors in ocean science and ocean governance (GOOS, IOC, WMO, among others), in order to undertake an in-depth and thorough examination of the possible ways to proceed, analysing the limiting factors and the leverage points, and exploring a diversity of approaches. This reflection process will call on the participation of other UN Ocean Decade programs such as Co-design, Foresea, CoastPredict, DITTO, OceanData-2030, and OceanPractices, as all of these programs aim at building a more efficient and fit-for-purpose ocean data system and are therefore the most directly concerned with addressing the systemic barriers that can stand in the way of success. This reflection process will also involve experts from outside ocean science (from public policy, business administration, economy, social and human sciences, private sector companies, etc.), in order to take into account a diversity of expertise and examine the problem under a number of angles: scientific, financial, political, cultural and organisational. The involvement of Early-Career Ocean Professionals (ECOPs) will also be key in this initiative, since ECOPs will be able to bring new perspectives and fresh original ideas to the discussion. Moreover, ECOPs are future leaders in ocean science and should thus be involved in shaping the future of that system.

This project will therefore undertake a transdisciplinary and multi-faceted approach in order to advance along the 10 dimensions described in this report and find game-changing solutions that integrate the social, political, cultural, scientific and economic aspects and take into account the complex interplay of factors. Moreover, for these solutions to be long-lasting and sustainable, they have to be adapted to local conditions (one size never fits all!) and be implemented at multiple levels and scales. The management structure of the project will therefore likely be a 2-dimensional matrix organisational structure, with one dimension being the pilot regions, and the other dimension being the transversal topics. During the first years of the projects, Task Forces will be created for grouping all experts working on the same pilot region, and Working Groups (WGs) will be created to bring together all experts working on the same transversal issue. Although these WGs will evolve as discussions progress, we can anticipate the following WGs:

WG1: ocean observing governance, for establishing a robust polycentric governance framework

WG2: science policy, for enhancing ocean governance and science policy coherence

WG3: financial governance, to evaluate financial needs and elaborate sustainable funding mechanisms

WG4: management/work organisation, for developing and implementing new forms of work organisation and organisational structures

WG5: cultural change and incentives, for developing new incentives and foster a cultural shift

WG6: communication, for increasing awareness on the importance and added value of integration and the vital role of long-term funding and sustained coordination support infrastructures

By transforming how the ocean observing systems are organised, managed and funded, this project will contribute to the transformational change the UN Ocean Decade is requesting. In particular, in addressing the cultural, organisational, financial and legal barriers that currently prevent the ocean observing system to better respond to societal needs, this project will strongly contribute to strengthening the capacity of the Ocean Decade Programs to fulfil their objectives. In particular, the programs Co-design, DITTO, CoastPredict, Foresea, OceanData-2030 and OceanPractices all aim at building a more efficient and fit-for-purpose ocean data system that better meet current societal needs. They will therefore considerably benefit from a more robust and modern organisation of the ocean observing system that enables better joint planning among partners and better integration among all its components. This project will thus enhance the capacity of these programs in building the transformational ocean science society needs today. Moreover, by examining not only the scientific aspect, but also the political, financial, cultural and organisational aspects that need to be rethought for the achievement of a truly integrated ocean observing system, this project is fully complementary to the other Ocean Decade projects, which tend to focus on the specific and sometimes narrow scientific and technological progress that is needed to better respond to a portion of current societal needs. However, as demonstrated in this report, there also exist significant systemic barriers that prevent the ocean observing system to become fully integrated and to adequately meet the challenges of our time. This project will thus aspire to move these issues forward and lead an organisational innovation in ocean observing, in order to overcome these barriers and implement the necessary organisational framework and cultural change for the ocean observing system to become more federated, transdisciplinary and integrated.

8. Conclusion

Achieving a truly integrated ocean observing system requires a profound change in our research and operational cultures and in the organisation of our ocean observing community. This change is of fundamental importance for both ocean science and society. This is timely since we now have the knowledge, the technical capacities, as well as urgent societal and political drivers to deliver "the ocean science we need for the ocean we want" (UN Ocean Decade, 2021–2030). The scientific community needs therefore to act in order to remove the barriers between ocean research activities and take full advantage of the scientific and technical advances made in the last decades. This evolution in the organisation of how we have been working so far in oceanography will not be easy, and will only be possible if scientists, institutions and funders embrace this change and collectively reflect on how to implement it. This work aims at being a first step opening the way toward more reflection. Our aim is to provide food for thought for further dialogue between all the parties involved on the concrete actions to undertake.

Notably, this study is limited by the author team's regional perspective, and only presents the view from the occidental science culture, since the barriers to integration might be different in other regions where the culture is different. In view of a worldwide integration, international dialogue would be needed to include more diverse perspectives and avoid "colonial science," also referred to as "parachute science" (e.g., Stefanoudis et al., 2021). Also, our expertise is mainly drawn from physical and biogeochemical oceanography, given that it is the area where real time observations are more advanced and modelling has reached good predictive capabilities, both allowing enhanced data assimilation and good initiatives to respond to societal and stakeholders' needs, along the value chain. However, we believe our approach could be largely applied to the other fields of ocean science, since the lack of coordination between teams and disciplines is a problem that is common to many basic and applied endeavours (i.e., Tress et al., 2006; OECD, 2020), and already reported in marine biological observations (e.g., Guidi et al., 2020).

We proposed here 10 lines of approach that we believe could lay the foundation of and stimulate a real transformational change in the internal organisation and the culture of ocean science. They would promote a working environment that is more conducive to innovation and the sharing of experience and expertise. To design this transformative change, we envision a 5-to-10-year UN Ocean Decade project that will continue this work and will aim at: 1) leading a collective process of reflection and discussion on how to implement these changes, involving a wide variety of different stakeholders, and 2) implementing these changes at multiple scales, and both at the international level and at the regional level, potentially starting with some selected pilot regions, to be later extended to the other regions of the world. This project will involve a wide range of experts, including the major players of the ocean observing system and experts from outside ocean science, in order to take into account a diversity of expertise and examine the problem under a number of angles: scientific, financial, political, cultural and organisational. The involvement of Early-Career Ocean Professionals (ECOPs) will also be key in this initiative, since ECOPs will be able to bring new perspectives and fresh original ideas to the discussion. Moreover, ECOPs are future leaders in ocean science and should thus be involved in shaping the future of that system.

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10. Annexes: some examples of integrated approaches

10.1. An integrated method for model skill assessment in the context of Search and Rescue

10.1.1. Introduction

Search and rescue (SAR) operators need the most accurate met-ocean forecast models to respond the most effectively to an emergency. In case of incident at sea, they run trajectory models, mainly based on Lagrangian discrete particle algorithms, to predict the drift of their target induced by the effect of ocean currents, waves, and winds and define a search area (Breivik et al., 2013; Barker et al., 2020). The skill of drift prediction is highly dependent on the accuracy of the met-ocean forecast data used to advect the Lagrangian model. In order to cover diverse spatiotemporal scales and guarantee near–real-time availability, different forecast products are made available to SAR operators. When all model predictions agree (i.e., their simulated trajectories are similar), there is a high level of confidence in the prediction, and the search area is reduced. But if different forecast models result in disparate trajectories, there are multiple viable outcomes, and the level of confidence decreases. Therefore, SAR operators need skill assessment methods to assess, within the shortest possible time, which model is likely to give the most accurate prediction at the moment and in the region of the incident.

In order to assess the skill of the models, field observations such as satellite-tracked drifters, satellite observations, moorings, and high-frequency radar (HFR) surface currents can all be used to estimate errors in the forecast outcomes. Usually, trajectories from drifter observations are used to evaluate the drift prediction accuracy (e.g., Thompson et al., 2003; Price et al., 2006; Barron et al., 2007; Brushett et al., 2011). However, drifter observations only provide an estimation of the model's performance along their drifting paths, i.e., over the area and during the time period when they are available. The reliability of this method thus strongly depends on the availability of trajectory observations at the location and at the moment of the incident, or shortly after it (near–real-time evaluation). As this is not always possible because of the scarcity of drifter observations in coastal regions (Tintoré et al., 2019), most of the time there is no alternative but to use the latest observations available in the region, which are not necessarily representative of the dynamics occurring at the moment of the incident. In this work, we therefore evaluated the possibility to use High-Frequency Radar surface currents to complement drifter observations for evaluating the ocean model predictions in these areas. Whereas drifters can only provide assessment along their drifting paths, and only when drifter observations are available, HFR data have the advantage to be continuous in space and time and to cover wide coastal areas, thus providing further information about the spatial distribution of the model performance.

This work is an example of integrated approach because:

- It has been designed in close collaboration with the users (in this case SAR operators) in order to precisely identify their needs and requirements, and has been fully focused to meet these needs
- It combines information from all available relevant data in the region (four numerical models + HFR data + drifting buoys), taking advantage of the strengths and weaknesses of each observing platform.

More information can be found in Révelard et al. (2021).

10.1.2. Data and methods

The data used to perform the simulations and to analyse the results are the following:

- **Surface drifters:** We use 22 drifters deployed in the Ibiza Channel during three experiments carried out by SOCIB (Tintoré et al., 2013, 2019) in the context of calibration exercises of the HFR system, in September–October 2014 (Tintoré et al., 2014), July–August 2016 (Reyes et al., 2020a), and November–December 2018 (Reyes et al., 2020b). (Figure 5).
- **High-Frequency Radar of the Ibiza Channel**: The HFR of the Ibiza Channel is part of the multiplatform observing system operated by SOCIB. The HFR system consists of two CODAR SeaSonde radial stations, transmitting at a centre frequency of 13.5 MHz with a bandwidth of 90 KHz (Lana et al., 2015, 2016). Hourly radial velocity maps (i.e., velocities toward or away from one antenna) from both stations are combined to form vector surface current velocities on a regular 3 × 3 km grid, with a range of up to 65 km from the shore.
- **Global and regional models**: Four ocean forecast systems available operationally in the Ibiza Channel are evaluated: the global model (Lellouche et al., 2018) from the Copernicus Marine Environmental Monitoring Service (CMEMS), the two CMEMS regional models of the IBI (Iberia- Biscay-Ireland; Sotillo et al., 2015) and MED (Mediterranean) regions (Simoncelli et al., 2014; Clementi et al., 2017), and the regional model of the Western Mediterranean Operational (WMOP) Forecasting System from SOCIB (Juza et al., 2016; Mourre et al., 2018).

The method used to evaluate the performance of the model in reproducing the trajectories is the Normalised Cumulative Lagrangian Separation (NCLS) distance, developed by Liu and Weisberg (2011), and defined as the cumulative summation of the separation distance between simulated and observed trajectories, weighted by the length of the observed trajectory accumulated in time. However, as a measure of trajectory model performance, the NCLS is counterintuitive to the conventional model skill scores as the smaller the NCLS value, the better the model performance. Thus, Liu and Weisberg (2011) proposed a new SS defined as follows:

$$SS = \left\{1 - \frac{NCLS}{n}, (NCLS \leq n)\right\}$$

$$0, (NCLS > n\ )$$

where n is a nondimensional, positive number that defines the tolerance threshold for no skill. This threshold corresponds to the criterion that the simulation is considered as having no skill (i.e., SS = 0) if the growth of the predictability error is larger than n times the mean flow displacement. Larger (smaller) n values correspond to lower (higher) requirements to the model. In general, n is set to 1. However, some studies selected the n value heuristically, in such a way that a small percentage of the SS values are negative and set to zero.

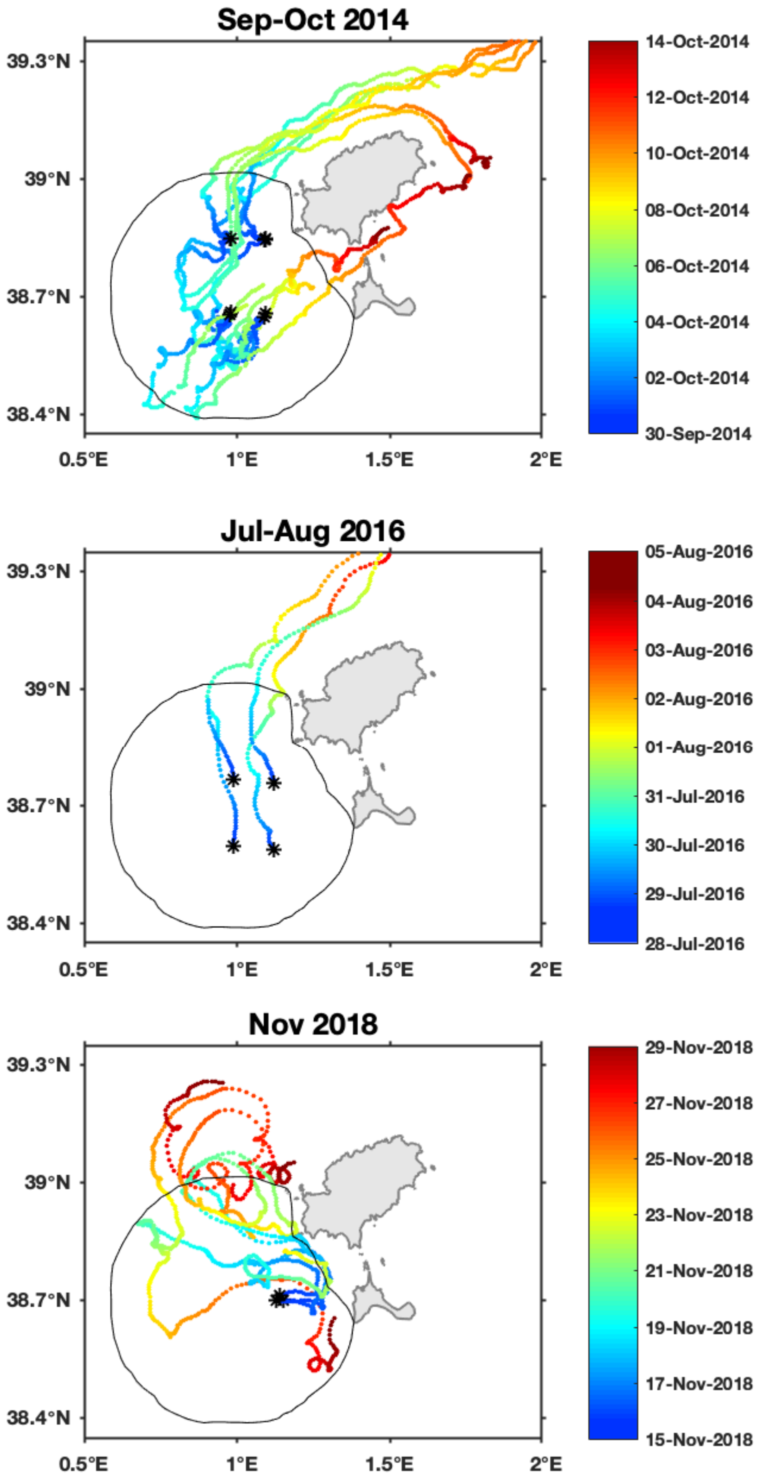

Figure 5: Maps of the trajectories of satellite-tracked drifters available in the Ibiza Channel from the experiments carried out in September-October 2014 (upper panel), July-August 2016 (middle panel) and November 2018 (lower panel). Black stars indicate start locations, and color shows the date associated with drifters' position, as indicated in the color bar of each panel. The black line shows the contour of the HFR gap-filled surface current coverage. From Révelard et al. (2021).

10.1.3. Results and discussion

First, the Lagrangian performance of the four ocean models is assessed using the 22 drifter trajectories. This analysis showed that the model performance is highly scenario-dependent and can exhibit highly variable SS values over the same region if the available trajectory observations sample different periods dominated by diverse dynamical conditions (not shown here). This highlights the need of developing skill assessment methods to quantify the models' performance in a systematic routine manner.

In a second time, we thus analyse the use of HFR-derived trajectories to evaluate the model performance. The methodology consists in selecting the HFR grid points where there is 80% of data availability during the period considered (as recommended by Roarty et al., 2012). We obtained 287 points in 2014, 338 in 2016, and 277 in 2018. Virtual particles are launched hourly from these grid points for a 6-h horizon forecast, and the trajectories simulated by the models are compared against the HFR-derived trajectories. In order not to mix different dynamics, we apply this method during a short time frame of 6 h. As an example, and for comparison with the results obtained using the drifters, we select the first 6 h of the experiments. However, we reach similar conclusions when computing the SS hourly during the first 3 days of observations instead of the first 6 h (not shown). For each experiment and each model, Figure 6 shows the spatial distribution of the temporally averaged SS*, which is defined as the SS, but without the imposition of the negative values to zero. We use a tolerance threshold of n = 1, and a lot of values obtained are negative. In order to not conceal the negative values and observe the spatial variability, the colour bar is adjusted to [−1 1].

Finally, to compare these results with the ones obtained using drifters, we compute the spatial average of the SS* over the areas covered by drifter observations during these 6-h periods. As the trajectories cover different regions in each experiment, the areas selected do not cover the same region nor have the same size in the three experiments (Figure 6 and 7). In 2018, the area selected is small because all drifters cover the same region during the period considered, whereas in 2014 and 2016, the trajectories are far away from each other. However, as the dynamics is quite consistent over the region (Figure 7), the area covering all trajectories is selected. Furthermore, similar results are obtained if smaller regions are selected (not shown).

Our analysis showed that the model ranking based on HFR-derived trajectories provides similar results to drifter observations (Table 2), demonstrating the great potential of this method for estimating the model's performance at operational basis. HFR could therefore be used in combination with the available drifter trajectories, if any. As HFR data are continuous in time, this method can be applied in near–real time, which is a strong advantage for evaluating extremely scenario-dependent models. This is a very promising result and opens up the possibility for implementing short-term prediction of HFR surface currents for SAR applications.

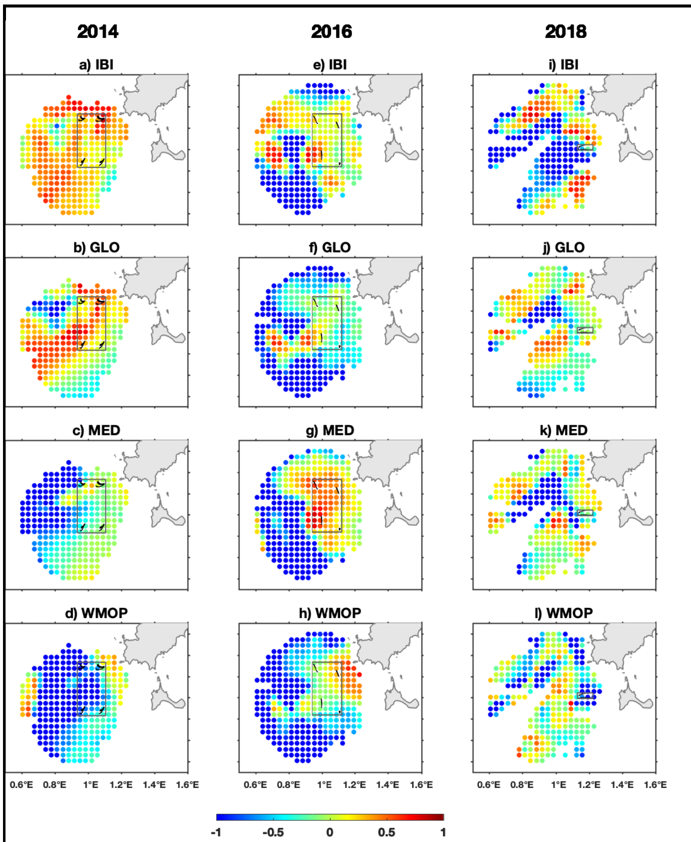

Figure 6: Temporally averaged Skill Score obtained for each model as indicated in the figure title by comparing against the HFR derived trajectories during a forecast time of 6 hours. Black lines show the drifter paths available during the same periods, and the boxes indicate the regions where the averages of Table 3 are applied. SS values are only obtained in those grid points with data temporal availability equal or higher than 80%.*

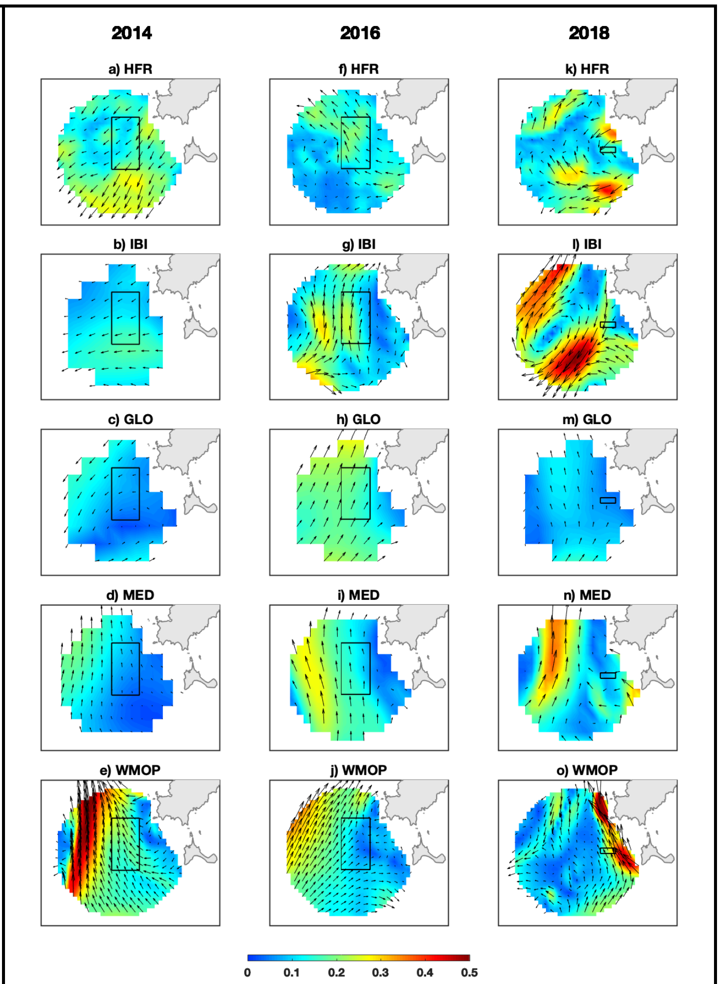

Figure 7: Temporally averaged surface current for each model and HFR OMA during the first 6 hours of the experiments, i.e. on 30-sept-2014 from 13:00 to 19:00 (left panels), on 29-July-2016 from 00:00 to 06:00 (middle panels) and on 15-Nov-2018 from 13:00 to 19:00 (right panels). The boxes are the same as in Figure 6 and indicate the regions where the averages of Table 2 are applied.

Table 2. Spatiotemporal average SS and their confidence intervals obtained after a forecast of 6h during the first 6h of experiment and over the boxes indicated in Figures 6 and 7, using real drifters and HFR-derived trajectories.*

	2014		**2016**		**2018**	
	Drifters (l=89)	**HFR** (l=50)	**Drifters** (l=28)	**HFR** (l=50)	**Drifters** (l=40)	**HFR** (l=23)
IBI	0.13 ± 0.07	0.30 ± 0.05	0.32 ± 0.14	0.13 ± 0.05	-0.45 ± 0.13	-0.36 ± 0.19
GLO	**0.21 ± 0.10**	**0.34 ± 0.05**	0.08 ± 0.20	-0.07 ± 0.05	**0.01 ± 0.02**	**-0.06 ± 0.01**

MED	0.01 ± 0.08	-0.21 ± 0.06	**0.55 ± 0.16**	**0.46 ± 0.04**	-0.08 ± 0.10	-0.16 ± 0.58
WMOP	-0.42 ± 0.14	-0.84 ± 0.13	-0.06 ± 0.21	-0.06 ± 0.06	-0.40 ± 0.04	-0.94 ± 0.27

10.1.4. References

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10.2. Integrated assessment of the coastal ecosystem of the South East Bay of Biscay

10.2.1. Introduction

This section presents a case study of the state of the art of applications of multidisciplinary integrated observations. In section 10.3 we present the steps towards the constitution of the Super Observatory **ebegi**, for the integrated assessment of the coastal ecosystem in the SE BoB. **ebegi** is constituted by different observational components (TOPICS). In this example, physical operational oceanography observations from the EuskOOS coastal observatory (https://www.euskoos.eus/en/; http:/doi.org/10.57762/t4wh-dq48) and data from the BIOMAN (http://doi.org/10.57762/n22g-wq88) oceanographic surveys, aimed at studying the effects of circulation on fish larvae, are used.

Transport and retention processes regulate the fate of early life stages (ELS; i.e. eggs and larvae) of different pelagic fish species in the BoB, such as the European anchovy (*Engraulis encrasicolus*), whose fishing activity is considered one of the pillars of the economy of the Basque fishing sector. Food availability and predation risk are important factors in anchovy recruitment, as are oceanic transport patterns. Transport patterns of ELS anchovies at seasonal scales show a southwest trajectory (Cotano et al., 2008; Irigoien et al., 2008; Uriarte et al., 2001). These patterns were deduced by comparing the positions of eggs, larvae and juveniles with the corresponding seasonal wind regimes or currents averaged over the area. To describe the advection of ELS anchovies more accurately, the Lagrangian approach provides insight into the effects of instantaneous advection as it describes the trajectory of a water parcel and its properties over time. Several studies have been conducted with this approach using hydrodynamic model current fields (Allain et al., 2001, 2007; Caballero et al., 2016; Huret et al., 2012) obtaining different ELS anchovies' transport patterns in the BoB in different periods.

In order to clarify what are the effects of circulation on the distribution of ELS anchovies, new Lagrangian simulations were performed based on multiyear observations of egg abundances and current velocities for peak spawning periods.

10.2.2. Data and Methods

The data used to perform the simulations and to analyse the results are the following:

- **Egg abundance to set the initial conditions.** Abundances were sampled at peak spawning periods (May) in the BIOMAN surveys, which are run every year in the BoB providing the most complete egg abundance distribution database. Abundances are sampled at 3 m and 10 m and therefore these are the depths at which the simulations were performed (herein surface and subsurface simulations, respectively).
- **Current velocities to force the advection.** At 3 m depth currents were provided by a high-frequency radar (HF radar) while velocities at 10 m were inferred from the 3D expansion of HF radar observations and an ADCP using a reduced order optimal interpolation (ROOI; Kaplan et al., 1997) method.
- **Model current velocities to set covariances (needed for applying the ROOI).** IBI_REANALYSIS_PHYS_005_002 product data (hereinafter IBI) provided by Copernicus Marine Environment Monitoring Service (CMEMS) were used as 3D velocity historical data to estimate the covariance matrix needed to 3D reconstruct horizontal velocities.
- **Chlorophyll-a (Chl-a) images to analyze the results.** Daily level 3 Chl-a images were obtained from the OCEANCOLOUR_ATL_CHL_L3_REP_OBSERVATIONS_009_067 product of CMEMS.

The ROOI method and simulations set-up are herein described:

- **ROOI method.** It uses historical spatial covariances between the observation points and the points where observations are going to be extended. Then, an EOF decomposition is applied to the covariance matrix and only the N leading modes are kept (ignoring higher-order modes). The reconstructed fields are obtained by extending the available observations to all the grid points based on those modes and by minimising the deviation between the reconstructions and observations. For a more complete description of the method see Kaplan et al. (1997), Jordà et al. (2016) or Manso-Narvarte et al. (2021).
- **Simulations set-up.** Simulations were performed from 2011 to 2018 (except 2015 due to the lack of data). Each simulation started from a scenario where 10,000 particles were released, distributed according to the egg abundance obtained during the BIOMAN surveys. Particles represented ELS anchovies passively advected. Trajectories were simulated for 30 days, which, is the period when larvae can be fairly considered passive particles (Irigoien et al., 2008; Cotano et al., 2008; Aldanondo et al., 2011). The ROOI velocities' availability depends on the simultaneous availability of HF radar and ADCP data, being scarce to cover the 30 days of the simulations except for the surveys of 2011 and 2013. Therefore, for these years surface and subsurface simulations were run forced by ROOI velocities. Additionally, surface simulations forced by HF radar velocities were run for all the above-mentioned years; thus, providing more simulations. Note that given the location of anchovy ELS along the water column the subsurface simulations are considered more realistic.

10.2.3. Results and discussion

First, the surface and subsurface simulations were compared in order to see how the surface simulations, which provide a wider time coverage, can represent the situation in the subsurface, which is more realistic. The results partly agreed, and surface simulations were used for interannual and feature-oriented analyses as a fairly good proxy for partially representing the transport patterns at 10 m depth, in order to have a wider time coverage.

Then, interannual differences (Figure 8) showed high variability emphasizing the influence of the different spatiotemporal scales of circulation on the transport, and therefore distribution. The centres of mass (CM) of the distributions did not get further west than the French slope (off the French coast), suggesting that most of the particles did not disperse toward the open ocean. In addition, higher coastal retention was observed when particles were initially located over the shelf instead of over the shelf-break, slope, or open ocean areas, stressing the importance of the spawning location in the subsequent retention.

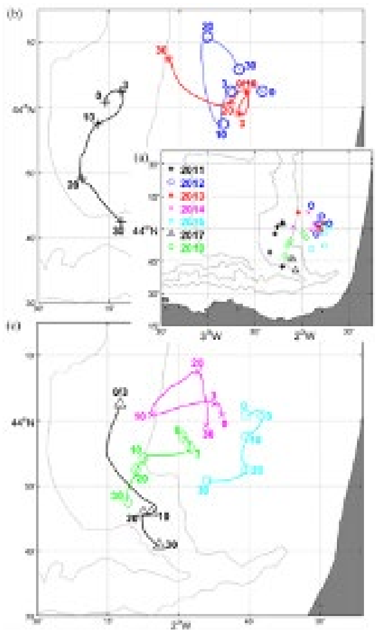

Figure 8. *(a) Location of the CMs at the surface for different years, (b) zoomed for 2011, 2012 and 2013. (c) zoomed for 2014, 2016, 2017, 2018. The numbers 0, 3, 10, 20 and 30 mean the days of simulation.*

As shown by the particle densities, Lagrangian coherent structures (depicted by Finite Size Lyapunov Exponents (FSLE)) and Chl-a images, eddies (example in Figure 9), fronts (example in Figure 10) and marked along-slope currents within the slope and Capbreton canyon areas (example in Figure 11) were identified as mesoscale features that can shape ELS anchovies' distribution. In some periods, a combination of several of these features along with the effect of the wind resulted in complex transport patterns. The impact that these kinds of features on the transport and retention patterns are in agreement with findings in the study area (Rubio et al., 2018, 2020) and also in other geographical areas (e.g. Sabatés et al., 2007b, 2013; Mullaney et al., 2013; Hernández-Carrasco and Orfila, 2018).

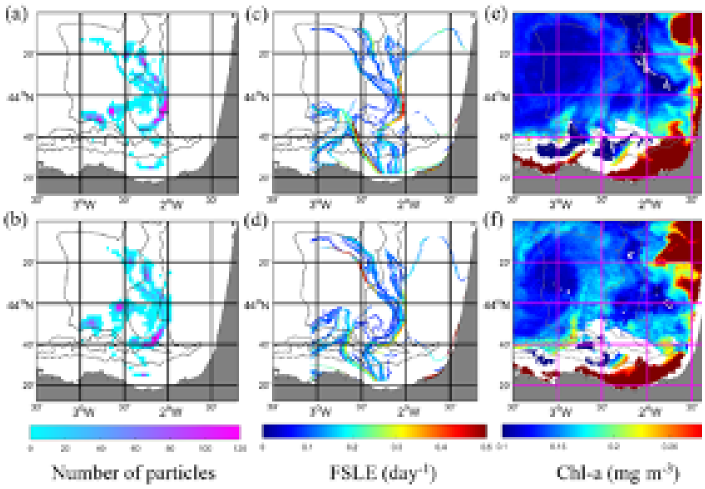

Figure 9. *(a, b) Simulated particle distribution, (c, d) FSLE (day^{-1}) and (e, f) Chl-a concentrations (mg m-3) in 2011 for 25 May (a, c, e) and 28 May (b, d, f) showing the eddy case.*

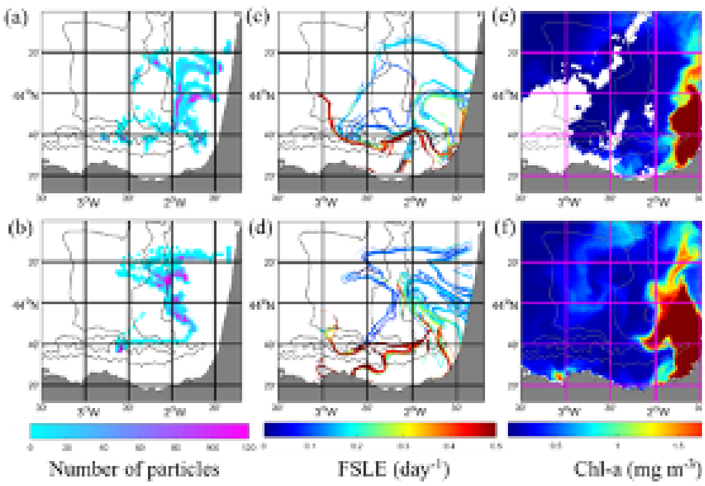

Figure 10. *(a, b) Simulated particle distribution (number of particles per simulation cell), (c, d) FSLE (day-1) and (e, f) Chl-a concentrations (mg m-3) in 2013 for 26 May (a, c, e) and 5 June (b, d, f) showing the front case.*

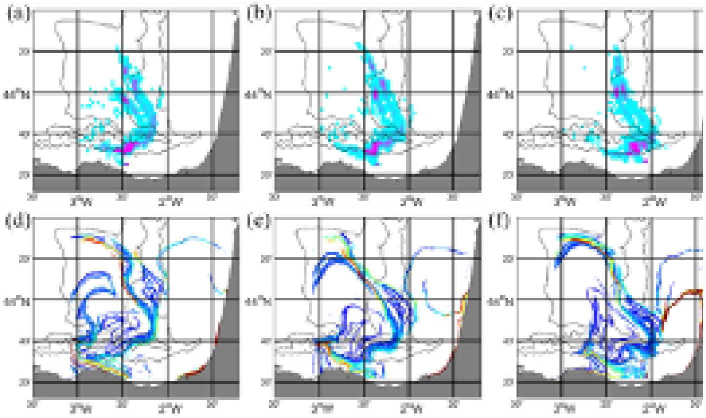

Figure 11. *(a, b, c) Simulated particle distribution, and (d, e, f) FSLE (day^{-1}) in 2011 for 1 (a, d), 5 (b, e) and 8 (c, f) June showing the case where particles are affected by the along-slope current.*

Besides showing an application of integration of multidisciplinary observations, this study showcases the potential of using observed and 3D reconstructed velocities (from observations) to study transport patterns, and the potential of integrated studies to address environmental or ecological issues and to better understand biophysical processes.

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10.3. Creation of an integrated dashboard for the Bay of Biscay

10.3.1. Introduction

AZTI (Marine Research Institute located in the Basque Country, SE Bay of Biscay), which has spent years playing a key role in monitoring the Bay of Biscay (BoB) marine ecosystem and the Basque Country coastal area, is promoting the creation of a Super Observatory in the SE BoB. In this section, we will showcase the main components of this observatory, called ebegi (standing for “e-vision” in basque) and describe the dashboard, topics, and the strategic actions ongoing towards the multiplatform and multidisciplinary integrations of its components.

10.3.2. Context

During the last decades and thanks to the participation in European, national, and regional projects, AZTI has played a key role in the monitoring of the BoB and the coastal zone of the Basque Country. Observational efforts, surveys, and initiatives (e.g., Coastal Operational Oceanography System EuskOOS, Climate Change Observatory, Network for the Ecological Quality Assessment of the Transitional and Coastal Waters, Multidisciplinary Ecosystem Surveys) currently respond to questions of different disciplines and sectors. In 2022, AZTI started the project ebegi with the aim to capitalise these efforts by ensuring better communication and coordination among the different components of the ocean observation in the area, for the development of a common scientific and technological strategy towards the constitution of an optimised observatory. One of ebegi 's main expected outcomes is to enhance the provision of Marine Ecosystem Data (both historical and real-time) that respond to the needs associated with ecosystem-based management and other demands in the fields of conservation and recovery of Biodiversity and Habitats, the challenges of Climate and Global Changes and the implementation of Policies and Directives on the management of the marine environment.

10.3.3. ebegi dashboard

The first development achieved within the framework of the ebegi project, was the development of the ebegi dashboard technological application (Figure 12), which integrates all the metadata of the existing measurement systems and activities in the area. This online application is a first step towards identifying additional measurement needs and integration opportunities to build an optimized observatory, which allows integrated and multidisciplinary observation of the marine environment and its ecosystem. The ebegi dashboard also provides visibility to the available information collected by AZTI for decades in its oceanographic surveys and observation activities, information that is key for the actors involved in the management of the marine environment.

Through the ebegi dashboard, one can explore and download the metadata of the multidisciplinary and multiplatform observational datasets at the core of the ebegi project.

The dashboard allows to:

- Explore the geographical coverage and extension of the different observational datasets, platforms, and networks.
- Visualise platforms by type, name, and measured variables.
- Select times and depths for filtering the active platforms in given periods or compartments.

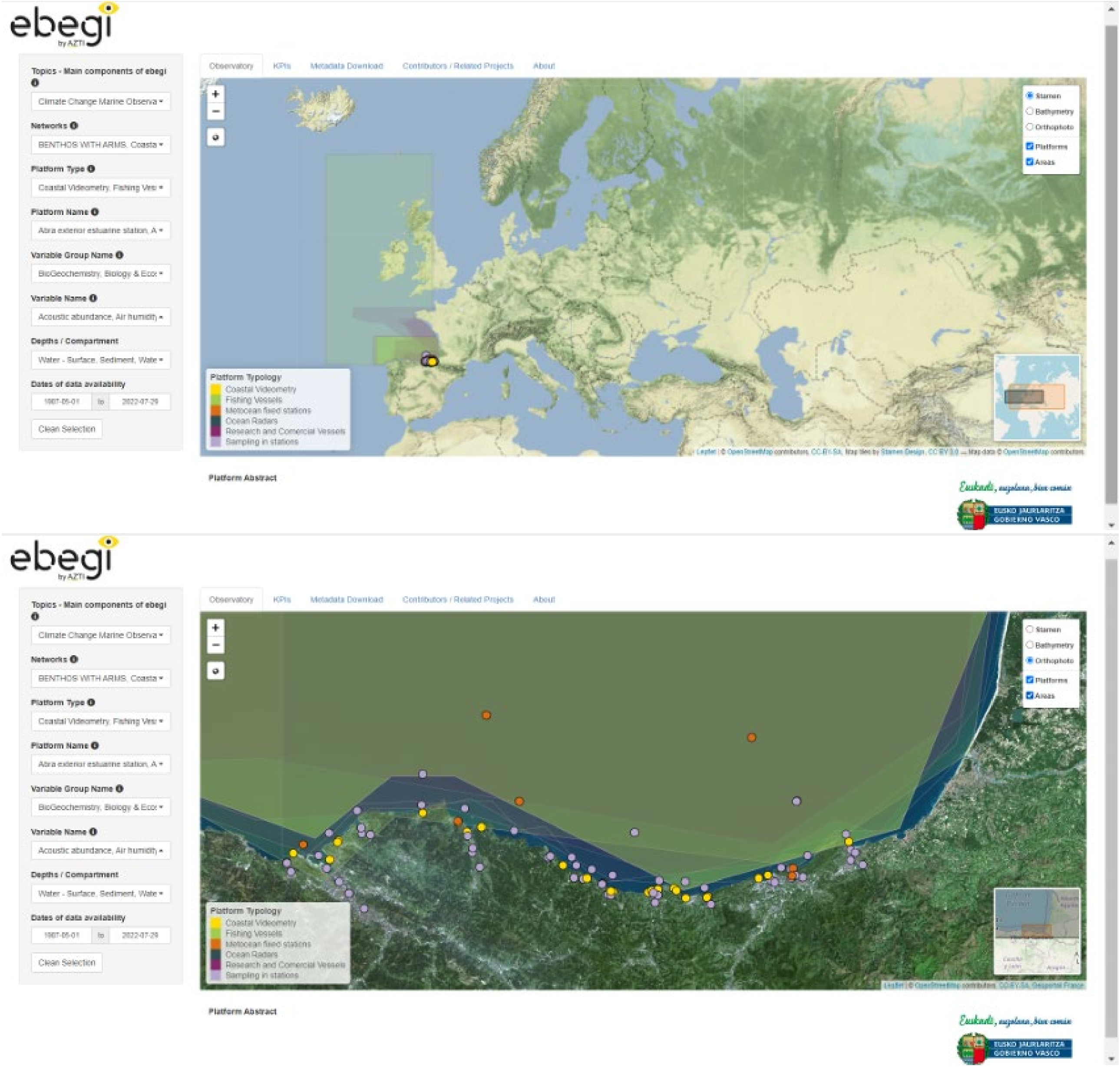

Figure 12- *Screen captures of ebegi dashboard: available at: aztidata.es/ebegi.*

10.3.4. ebegi topics

The TOPICS are generally associated with issues or components that give rise to monitoring programs, long-term projects, etc. They constitute the first level of organisation in the structure of ebegi and are intended to help users to orient their search. These topics are summarised in Figure 13. The type of observational approach and platforms used depend on each of these TOPICS and encompass:

1. Coastal videometry systems
2. Opportunity observation from Fishing vessels
3. Meteocean fixed stations
4. Ocean radars
5. Research and commercial vessels

6. Sampling in stations

The variables measured by the ensemble of TOPICS are shown in Figure 14.

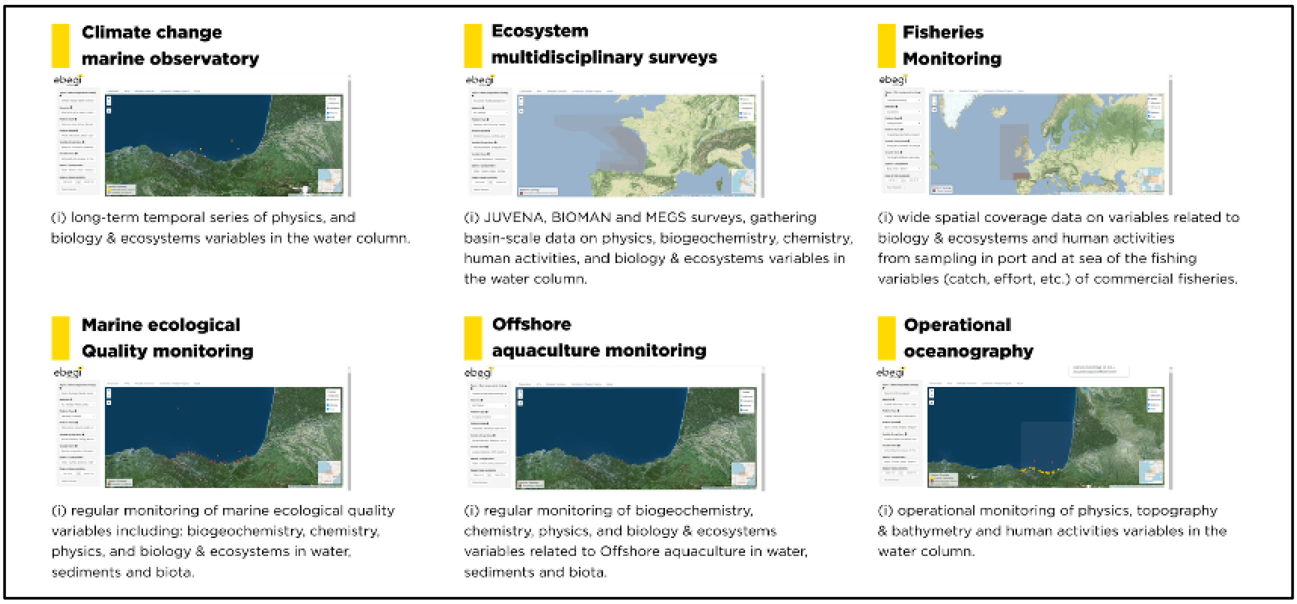

Figure 13- *Schematic view of ebegi TOPICS. The Topics constitute the first level of organization in the structure of ebegi.*

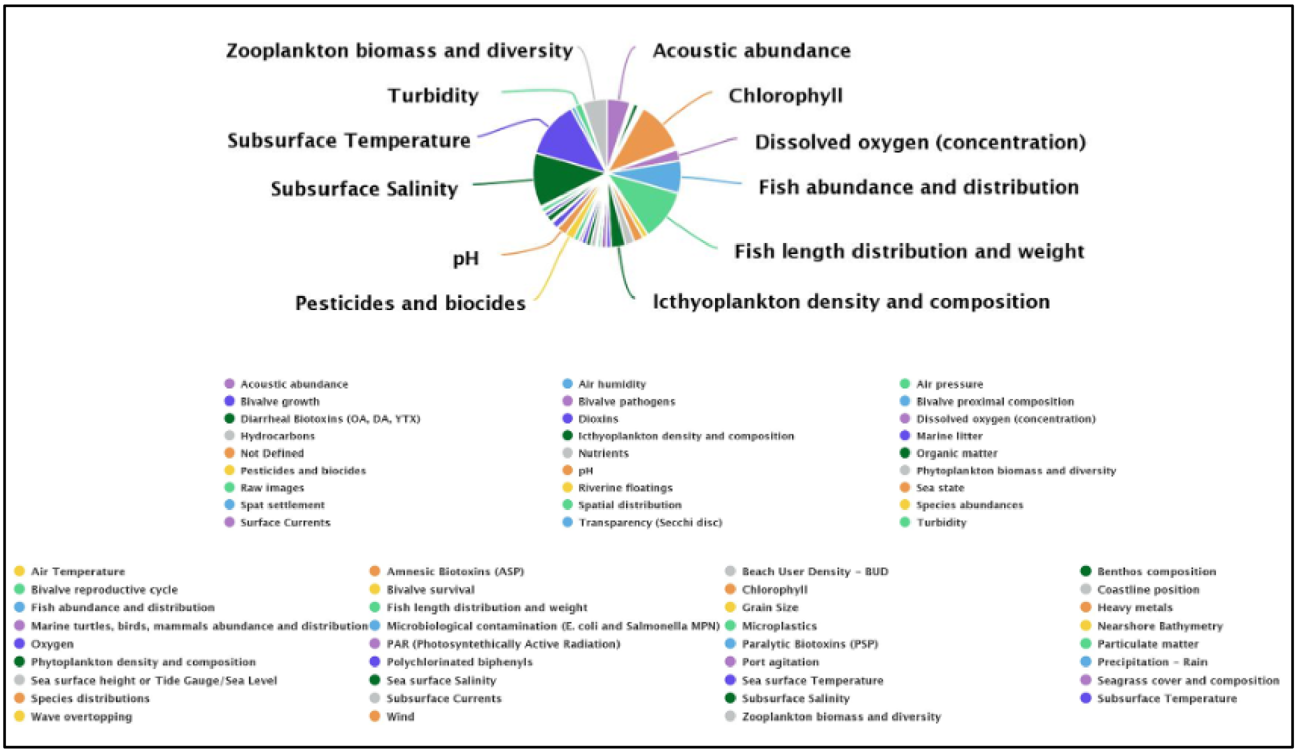

Figure 14 *– Variables measured by ebegi Super Observatory, the most common ones (by number of measuring stations/surveys or locations of continuous monitoring) are highlighted in the upper panel.*

10.3.5. ebegi strategy

The ebegi Super Observatory design and future strategy are based on the following principles:

1. Reinforce multiplatform and multidisciplinary sampling strategy.
2. Provide response to scientific questions and societal needs: co-design of integrated coastal data products and services.
3. Ensure continuous and sustained observations over time.
4. Enhance links with communities of existing activities, both technical (modelling) and sectoral (fishing, tourism…).
5. Recognize the transnational nature of the region (since the phenomena studied transcend administrative borders).

Its development is organised in five work packages, covering different aspects, from strategy to experimentation, in a 7-year work plan initially conceived for the period 2022-2029:

1. **Scientific and observational strategy**
    a. Analysis and definition of the components, diagnosis of the current state and development opportunities.
    b. Improvement and maintenance of ebegi dashboard.
    c. Definition of common scientific objectives and integration opportunities.

2. **Technological and Methodological Innovation**
    a. Technological surveillance and definition of objectives.
    b. Development/Implementation of innovative sensors or sensor packages.
    c. Data Science methodology improvements for data processing and integration (e.g. machine learning).

3. **Pilot experimentation**
    a. Definition and prioritisation of pilot projects.
    b. Experimental design of selected pilot projects.
    c. Execution of pilot projects and exploitation of technological and scientific results.

4. **Publication of FAIR data and co-design of data products**
    a. Promotion of open data publication and the use of DOIs for ebegi components and outputs (data and data products, software, documentation).
    b. Co-design and development of new data products (mainly oriented to Marine Strategy Framework Directive MSFD and fisheries).

5. **Coordination and communication**
    a. Promotion of the Super Observatory in the fishing sector and other sectors.
    b. Dissemination of the scientific results.
    c. Connection with regional, national, and international observation and data infrastructures.

Section 10.2 presented a case study of the use of data from different ebegi components for the study of early life stage anchovies transport in the area. Other examples of integrated experimentation in 2022 have been:

(i) A multidisciplinary glider survey in October, with the objective to monitor the migration of anchovy juveniles in the Cantabrian Sea (https://www.azti.es/en/xixili-the-underwater-glider-that-keeps-watch-over-our-waters/) and (ii) two drifter surveys, conducted in May and October for the study of floating marine litter transport and the role of submesoscale fronts in the aggregation of marine litter at sea.