

Project information	
Project full title	EuroSea: Improving and Integrating European Ocean Observing and Forecasting Systems for Sustainable use of the Oceans
Project acronym	EuroSea
Grant agreement number	862626
Project start date and duration	1 November 2019, 50 months
Project website	https://www.eurosea.eu

Deliverable information	
Deliverable number	D9.3
Deliverable title	Ocean Observing Needs
Description	This report summarizes the needs to further improve the ocean observing and forecasting system after four years of the EuroSea project. Even though EuroSea has achieved many things, the project partners have identified future needs and paths forward towards the EuroSea vision - a user-focused, truly interdisciplinary, and responsive European Ocean Observing and Forecasting System, that delivers the essential information needed for human wellbeing and safety, sustainable development and blue economy in a changing world.
Work Package number	WP9
Work Package title	Project Coordination, Management and strategic ocean observing alliance
Lead beneficiary	GEOMAR
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Due date	30.06.2023
Submission date	30.09.2023
Comments	



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 862626.

Table of contents

Executive summary.....	1
1. Introduction.....	1
2. The Ocean Observing Value chain.....	3
2.1. Input	3
2.2. Process.....	3
2.3. Output	3
2.4. Impact.....	4
2.5. EuroSea Contributions.....	4
3. Governance and Coordination of ocean observing and forecasting systems	4
4. Ocean Observing System Design	5
5. Network Integration and Improvement	6
6. Data integration, assimilation and Forecasting.....	7
7. Conclusion	9

Executive summary

The EuroSea project was constructed around the ocean observing value chain. Just as intended, the value chain concept is a useful prism for designing the ocean observing and forecasting system, or, indeed, a project like EuroSea that set out to improve just this system. Indeed, several projects in the past have successfully used the value chain for this purpose, for example the AtlantOS EU-funded project or the TPOS 2020 project. In this report we summarize some of the main take home messages from EuroSea on the technical innovation and data management needs for the European Ocean Observing and Forecasting System. This report does not set out to summarize EuroSea outputs or impacts, but rather look forward on what we still have to accomplish. We do so, using the prism of the ocean observing value chain, and articulate needs in the areas of governance and coordination, design, network integration and, finally, data integration, assimilation and forecasting. This report is not a detailed list of immediate needs and next steps, but rather a compilation of the broader technical needs for the observing and forecasting system and is meant as a broad guide to the community and possibly to funders of a possible path forward.

1. Introduction

The ocean affects humans in many ways, regardless of where we live. It is the primary regulator of the global climate that makes this planet habitable. It provides humans with food, materials, energy, transportation, and recreation. The ocean is also a source of many potential hazards, both natural and anthropogenic, including increasingly strong hurricanes and severe coastal flooding, tsunamis, storm surges, sea level rise, harmful algal blooms and other man-made pollution. Extreme events will intensify and increase in accord with climate change. The ocean is facing many stressors that ultimately affect the human population as well, such as warming, heat waves, overfishing, changing circulation, ocean acidification, and pollution that all compromise the very ecosystem that humanity relies on for oxygen, water, food, medicines, climate regulation, and more. In face of these stressors and threats to the ocean, most of them directly relevant to the well-being and prosperity of society, information and knowledge about the ocean, changes and vulnerability is needed to support and inform management of the ocean space. As new actors are active in the ocean with additional requirements, the demand for ocean reliable and regular information and forecast is steadily increasing.

Although the capacity to deliver ocean information has increased during the last decades, Europe still has fundamental gaps in the ocean observing and forecasting capacity, limiting the ability to sustainably manage the ocean and its resources. A sustainable and adequate ocean observing and forecasting system needs integration and coordination of national efforts towards an international system. Such a programme would need to coordinate the deployment of ocean observing efforts, ensure data sharing for proper access and interoperability, and support timely delivery of ocean knowledge and information for science-based management and the Blue Economy.

This report sets out to summarize some key findings of the EuroSea project as a strategic report for the technical innovation and data management needs within Europe. It should not be seen as a summary of all activities conducted within the EuroSea project, but rather as a guideline for future activities and engagement, focusing on technical innovation and data management needs. The structure of this report

reflects the value chain of ocean observing as defined in the Framework for Ocean Observing (FOO¹, Figure 1) and slightly differently in the Global Ocean Observing System (GOOS) 2030 strategy² (Figure 2). Those two figures are not contradicting each other at all, but the FOO version has some more details, and is possibly more targeting the science community, whereas the version from the GOOS strategy takes a slightly higher-level view. The value chain concept also guided the structure of the EuroSea project into work-packages with targeted goals.

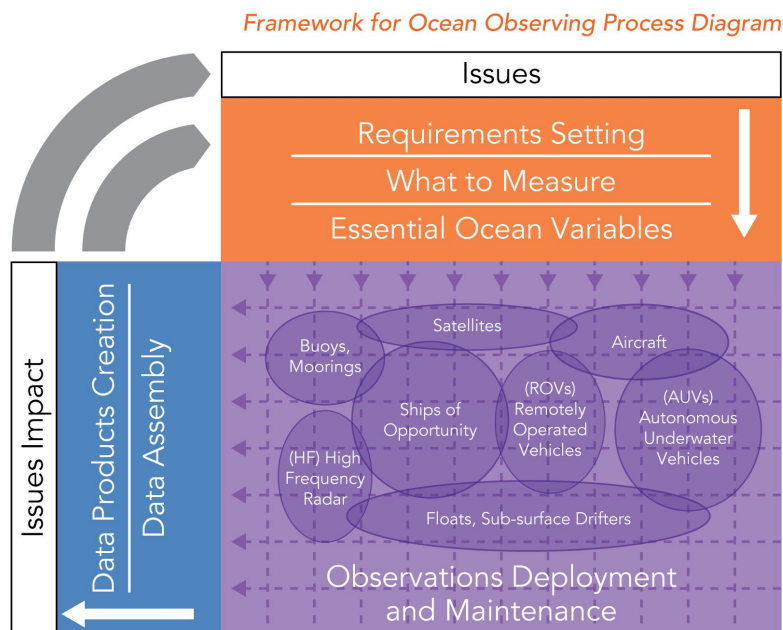


Figure 1. The ocean observing value chain as it is described in the Framework for Ocean Observing

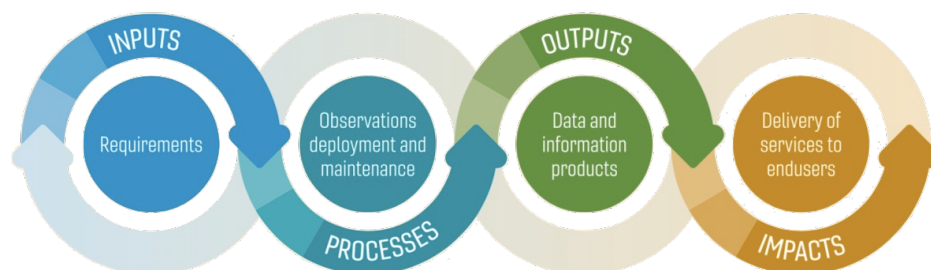


Figure 2. The ocean observing value chain from inputs, through processes and outputs to impact. From the GOOS 2030 strategy.

¹ Lindstrom, E., Gunn, J., Fischer, A., McCurdy, A., Glover, L., Alverson, K., et al. (2012). A Framework for Ocean Observing. By the Task Team for an Integrated Framework for Sustained Ocean Observing. Paris: UNESCO. doi: 10.5270/OceanObs09-FOO

² The Global Ocean Observing System 2030 strategy. IOC, Paris, 2019, IOC Brochure 2019-5 (IOC/BRO/2019/5 rev2), GOOS Report No.239

2. The Ocean Observing Value chain

2.1. Input

The ocean observing value chain defines the initial step as the *input*, i.e. the requirement setting, that defines the reason for the investment in the observation, i.e. what are the questions or issues we would like to understand better and monitor over time. For instance, we could articulate a need to understand the oxygen distribution in the ocean. Depending on why we are interested in oxygen, the need could be defined as oxygen concentrations in particular areas, or the extent of areas with suboxic conditions, the length and duration of suboxic (or even anoxic) events, or similar. Such information will be important to understand impact on ecosystem, can guide fishery policy and quota, and forecasts on this could enable management options for aquaculture, just to mention some. The next step in this procedure is to define, in practical terms, what kind of observations are needed to get to this information. In this example, oxygen concentration is an obvious candidate to observe, but there are other variables that are needed. Obviously, one need to define both spatial and temporal distribution of the observations, as well as the required precision and accuracy of the measurements.

The Essential Ocean Variables (EOVs) concept is a critically important link in the ocean observing value chain. EOVs have been defined by the Global Ocean Observing System (GOOS) and are based on analysis of impact vs. feasibility. Interaction with model data-assimilation schemes is needed in this step, and this should be guided by Ocean Observing design experiments, Observing System Simulation Experiments (OSSEs) and observing system experiments (OSEs).

2.2. Process

The second step in the value chain is defined as the *process* step where ocean observing assets are deployed and maintained. Here we see the many options to measure one particular EOV, all with different attributes that should be matched to the requirements defined in the first step. The example of oxygen reveals that there are several different options to measure oxygen on different platforms using different sensors, or by taking water samples and using well-established wet-chemical methods to accurately determine the concentration of oxygen³. Depending on what aspect of ocean oxygen, or ecosystem health, one is focusing on, the choice of platforms and sensor/instrument will vary. One important aspect of an *integrated* ocean observing system is to weigh different priorities and goals to optimize the synergy between different users and stakeholders. This requires a constant dialogue between the actors, and a significant amount of coordination and negotiation between the actors and funders of the observing elements. Technical innovations leading to more accurate and precise sensors that can be used on novel platforms, i.e. increased feasibility, as well as changing requirements, i.e. re-assessment of impact, are considered in the evolution of EOVs.

2.3. Output

The third step of the value-chain is the *output* of data, data-products and information. Effective data management systems are essential to ensure that essential data are not only collected but also retained and made accessible for analysis. Adhering to the FAIR (Findable, Accessible, Interoperable, Re-usable) principles

³ Grégoire, M., et al. (2021), A Global Ocean Oxygen Database and Atlas for Assessing and Predicting Deoxygenation and Ocean Health in the Open and Coastal Ocean, *Frontiers in Marine Science*, 8(1638), doi:10.3389/fmars.2021.724913.

is critically important for a functional ocean observing and forecasting system. The additional attributes of free, timely, and unrestricted delivery of ocean data is beneficial for both originators and users, and enables development of novel information and forecasts products.

2.4. Impact

Ultimately, the aim of these activities is obviously to achieve (hopefully positive) *impact* through delivery of services and information to end-users. This is where a constant feed-back process should take place to assess the impact of the output vs. the initial issue identification.

2.5. EuroSea Contributions

All of these aspects have been addressed by EuroSea. The EU funded project EuroSea was running between late 2019 and the end of 2023, consisting of more than 50 partners from 16 nations, representing research institutions, agencies and private sector partners. EuroSea has strengthened the cooperation between science and industry, politics and the public with the common goal of a sustainable blue economy and the responsible handling of the sensitive marine ecosystems. The project has made significant contributions towards generating, processing and linking information about our oceans, and the long-term use of this and the resulting knowledge in a wide variety of areas. The vision of EuroSea is to advance research and innovation towards a user-focused, truly interdisciplinary, and responsive European Ocean Observing and Forecasting System that delivers the essential information needed for human wellbeing and safety, sustainable development and blue economy in a changing world. In order to significantly improve European ocean observation and forecasting services, EuroSea has been working closely with developers and potential end-users of products and services. This co-design approach led to the strengthening of a joint community which is needed for the design and the implementation of a functional system. The overall aim of EuroSea is not only to significantly improve the European ocean observing system which advances scientific knowledge about ocean climate, marine ecosystems, and their vulnerability to human impacts and demonstrates the importance of the ocean for an economically viable and healthy society by delivering ocean observations and forecasts but also to integrate this system as an important entity in the global context.

3. Governance and Coordination of ocean observing and forecasting systems

Our capacity to effectively manage the ocean observing and forecasting system is limited by insufficient coordination and governance at national, European and international levels. Since there is a myriad of different actors making ocean observations or being involved in other parts of the value chain, coordination of activities is essential. The need for coordination reaches across the entire value chain, and is particular critical for the process step with a multitude of actors, both governmental, academia and private sector conducting ocean observations. The number of actors delivering forecasts is smaller, but coordination and communication is essential for increased efficiency of the system. For the *in-situ* ocean observing system, GOOS is the leading body of global coordination, supported by a network of Regional GOOS Alliances (GRAs). In Europe, the acknowledged GRAs are EuroGOOS as well as BlackSeaGOOS and MOONGOOS, although both of the former are closely associated to EuroGOOS. In addition, the European Ocean Observing System (EOOS) has been articulated to effectively broaden the scope and to align with the GOOS-2030 strategy. Although currently largely and unfunded activity, EOOS “takes a broad and inclusive perspective of the observations and stakeholders within its scope. It strengthens coordination and dialogue between all those planning, resourcing, managing, implementing, and aggregating ocean observations at European, regional, national

and subnational scales” (EOOS strategy 2023-2027)⁴. The needs of EOOS and GOOS, and recommendations for these bodies from the EuroSea project are articulated in the EuroSea Deliverable D1.8⁵. The long-term aim of EOOS should be to streamline ocean observing coordination and support across Europe and to maintain the strong link to the global system.

The situation is similar for the ocean forecasting system where international coordination is guidance by the expert team on Operational Ocean Forecast Systems (ETOFS, one of GOOS components), focusing on the operational aspects of ocean forecasting, and OceanPredict⁶ that takes on a role in the development of ocean forecasting systems.

4. Ocean Observing System Design

A properly designed ocean observing system, based on the requirements of the end-users and the forecasting system, is important to increase the efficiency and utility of the system. Such a design is a great advantage when it comes to coordinating and implementing the system, normally operated by a multitude of actors. Although relatively straight forward, but not an easy task to design a single observing network. It is a difficult task to design an observing system for observing one single phenomenon, or EO, across different platforms and sensors. It is a daunting, if not impossible, task to design an observing system across multiple networks for all EOs. Certainly, a bit of pragmatism is useful, realizing that the “enemy of good is perfection”, and implement an iterative process where the impact is measured in relation to the requirement setting is already foreseen in the FOC value-chain. One example of a global network with a careful design is the Argo network, and the adaptation to technical progress articulated in the one-Argo design that has, among others, added BGC-Argo (floats with biogeochemical sensors) and deep-Argo (floats with capacity for 4-6-thousand-meter-deep cycling). The Argo design is also, to some extent, co-designed with in particular the GO-SHIP repeat hydrography network.

In EuroSea work was conducted where BGC Argo float observations were used for model evaluation and for identification of ocean regions with large forecast errors and regions that should be better sampled to allow for better accuracy estimation. Using the BGC model simulation, regions that contribute the most to the export of carbon were also identified and might be the ones where BGC Argo deployment could be critically important. Similarly, EuroSea conducted designs aimed to reconstruct fine-scale ocean currents (~20 km) to validate SWOT satellite observations by integrating different in-situ platforms. Such design experiments are clearly useful to improve the utility of the networks and increase the effectiveness of *in-situ* observations.

We recommend to conduct targeted design experiments for an optimal integrated *in-situ* observing system. We also recommend that such experiments consider the feasibility of the system, e.g. the cost and precision of the measurements. For instance, surface ocean carbon can be measured with expensive instruments that measure carbon to high precision, or with less expensive instruments that measure carbon less precise. What is a useful (ideal) mix of expensive and not-so expensive instruments and platforms to reach a pre-defined target of, for instance, constrain the air-sea flux to +/- 10% on annual time-scales (which is the target articulated in the GCOS Implementation Plan) with a finite budget (they all are)?

⁴ <https://www.eoos-ocean.eu/wp-content/uploads/2023/02/EOOS-Strategy-2023-2027.pdf>

⁵ <https://eurosea.eu/deliverables/>

⁶ <https://oceanpredict.org/>

Future needs include implementation plans for the ocean observing system that are concrete enough to be fundable and implemented. It will be impossible to come up with a perfect plan (they don't exist), and both requirement and the technical capability are constantly evolving. More important would be to focus the design on a few key phenomena, such as the ocean carbon uptake, and design a plan that is regularly refined and updated. This is an iterative process, and needs to involve funding agencies and stakeholders in the evolution of such plans. An example of such a process was exercised in the TPOS 2020 project that ultimately led to a design of the Tropical Pacific Observing System⁷.

5. Network Integration and Improvement

The second step in the value chain is the *process* step, i.e. the deployment and maintenance of observational platforms and sensors used to measure EOVs in the field. As mentioned before, EOVs can mostly be measured on a variety of different platforms and by different sensors. Ideally, these observations are coordinated for efficiency of operation, and there are agreements of best practices and standards. DeYoung et al., (2019)⁸ defined two main coordination mechanisms, both of which would be part of the Global Ocean Observing System. Firstly: Ocean observing *networks* are typically platform- or theme-focused organizations, or groupings. Globally, the networks are overseen by the Ocean Coordination Group (OCG) of GOOS, that have set up a set of attributes⁹ needed to qualify as a network. Similar structures are set up on regional scale, for instance by EuroGOOS, where they are called Task Teams, and as a part of the EOOS framework.

The articulated attributes have been, and are, important to evolve the networks towards higher readiness levels, and are one of the guiding criteria for the evolution of the observing system. Secondly: *Ocean observing Systems* that are large scale national, regional or international programs that build on observing networks within a region. EuroGOOS would be an example of such a system, and the overarching goal of this report is to discuss its technical needs.

The networks are critically important for the implementation of the observing system, and EuroSea has supported the advancement of eight different networks. These are all at slightly different readiness level, and thus their immediate needs are all different. These are reported on in D3.2, for an initial assessment, and in D3.18¹⁰ for an assessment near the end of the project. For details we would refer to those, and other reports produced by WP3 of EuroSea. The assessments in, in particular, D3.18 is very valuable for guiding investment needs in the various networks. Common attributes that needs to be considered are 1) the level of coordination within a network, 2) the availability of community agreed on Best Practices, 3) the level of integration of the network in the observing system, and finally 4) the data delivery, including meta-data standards, FAIR conformity etc. Going into some more detail EuroSea D3.18 assessed to what an extent a network had a website for communication, if the network had established a governance system and articulated terms of reference, if the network is integrated in EU led observing efforts, and to what extent the European networks were linked to the global network. Most of the existing networks were well advance on these points.

⁷ <https://tropicalpacific.org/>

⁸ DeYoung, B., Visbeck, M., de Araujo Filho, M. C., Baringer, M. O. N., Black, C., Buch, E., ... & Willis, Z. (2019). An integrated all-atlantic ocean observing system in 2030. *Frontiers in Marine Science*, 6, 428.

⁹ https://www.goosocean.org/index.php?option=com_oe&task=viewDocumentRecord&docID=33315

¹⁰ <https://eurosea.eu/deliverables/>

Most networks are implementing the use of Key Performance Indicators (KPIs) to monitor progress, although this is for some networks still in development, and common KPIs across networks should be implemented to foster integration and comparability. While science and operational services are strong drivers for all networks, the wide mixture of funding sources, often short-term and project driven, makes long-term planning difficult. In fact, even the “sustained” ERICs, rely heavily on short term funds from projects, for a significant part of their activity.

During the assessment, the often poor connection between platform-oriented networks and thematic networks, such as the Integrated Carbon Observation System (ICOS¹¹), was particularly noted as in need for increased efforts, ideally centrally coordinated. Another topic that needs further attention, although significant progress has been made during the EuroSea time (supported also by other projects and efforts) is the *integration* between networks towards coordination, design and observations of EOVs across networks.

We also note that there are a number of networks that are seen as aspirational, i.e. they are in very early stage of readiness, and there are observing systems that are not at all organized. There is a need to increase the number of ocean observing networks for increased integration and efficiency to observe and report on all EOVs on a global scale. This need is in particular large for the biology and ecosystem networks, and EuroSea has advanced a few of those towards better coordination. We recommend to support the ocean observing community to form networks that comply to the attributes articulated by OCG. We also recommend integrating several more coastal monitoring programs in such networks; there is a larger potential for increased synergy and efficiency of the system in doing so.

6. Data integration, assimilation and Forecasting

No matter how well the requirements have been thought through, and how sophisticated the observations of an EOv are; the effort is useless unless that data is available. The data should ideally be delivered along the FAIR principles (Findable, Accessible, Interoperable, and Re-useable) for technical reasons. I will not go into details here, but refer to literature, e.g. Wilkinson et al., 2016¹², Tanhua et al. 2019¹³.

Other important attributes include having free data, at least for data funded by public resources. It is a very interesting discussion on how the observing system can engage external partners in taking ocean observations, and how that should be rewarded by either a monetary reward for making the observations, or as an enterprise selling the data. The players are still finding the way around this topic and it is not likely to come to a conclusion anytime soon, and in reality, we will have different systems in place simultaneously. EuroSea tested one such “pay-for-data” scheme in that we hired the company Saildrone to make a mission in the tropical Atlantic to measure pCO₂ from an autonomous surface vehicle; the evaluation of the data and the benefit of this model vs. more traditional science operated approaches is still on-going in EuroSea. We note though, that since the ocean is vast, and the need of more data from the ocean is large, an efficient

¹¹ <https://www.icos-cp.eu/>

¹² Wilkinson, M. D., et al. (2016), The FAIR Guiding Principles for scientific data management and stewardship, *Scientific Data*, 3, 160018, doi:10.1038/sdata.2016.18.

¹³ Tanhua, T., et al. (2019), Ocean FAIR Data Services, *Frontiers in Marine Science*, 6(440), doi:10.3389/fmars.2019.00440.

ocean observing system is nothing that the science community cannot do alone, and we need to build strong ties to the private sector and the public to support the observing efforts.

Another important attribute of data delivery is the latency. Traditionally, many data streams are delivered in delayed mode, sometimes years after the observations were taken – a practice usually in-line with the demands for scientific research and the demands from science funding agencies. This is however less useful for the sustained observing system where there is a clear need to deliver data in real-time, near real-time, or at least as soon as possible, for the sustained ocean observing system.

The observing community is generally getting accustomed to deliver data to repositories faster, and one of the reasons for this is improved data management infrastructure in Europe, that facilitates the submission and curation of the data. It should however be noted that the increasing variability of ocean data makes efficient curation and quality control of the data challenging. Very often though, there is no incentive for scientists to deliver data in near real-time mode (nRT), and hence only preliminary quality controlled, to operational data centres as this is most often not part of the science project that funded the mission. Nevertheless, the utility of nRT data delivery is being more recognized by the ocean science community, and data centres have increased the capacity to handle nRT data, leading to improved data delivery times. That being said, there is still large room for improvement when it comes to latency of data delivery.

The ocean forecast system is, on the very basic level, based on ocean modelling and assimilation of observations into those models. Good progress in ocean forecasting has been made thanks to increased computer capacity and a wealth of satellite data that are assimilated into ocean forecast models of increasing resolution. Although being the key to assimilation, satellites provide very little information of structures and the state of the interior ocean. This is true for the physical state of the ocean, but maybe even more so for biogeochemistry and for biology. There is a distinct need to assimilate *in-situ* ocean data to the ocean model and forecasting system.

EuroSea has progressed the assimilation of different *in-situ* data sets into the Copernicus Marine Environment and Monitoring Service (CMEMS) ocean analysis and forecasting system. But there are many observations that are still not assimilated. It is only via an integrated approach that different observations can efficiently constrain the different scales of variability of the ocean. For instance, the satellite observations bring higher spatial resolution between the tropical moorings, but only for the ocean surface, the tropical mooring and Argo profile data assimilation constrain the larger scale ocean thermohaline vertical structure (EuroSea D2.2¹⁴; Gasparin et al., 2023). The representation of the high frequency signals observed at mooring location significantly improved in the model analysis compared to a non-assimilative simulation. Similarly, activities in EuroSea assimilated BGC-Argo data, which significantly improved the model's ability to reproduce the North Atlantic bloom. Assimilation of *in-situ* data streams are dependent on timely delivery of data with well-known attributes and with some degree of sustainability to them. In addition to data delivery and assimilation, there is a need to improve the models, in particular for biogeochemistry and biology as these tends to be less well developed.

We recommend improvement along the data delivery chain to data centres of EOVS and increased capacity to assimilate these data into operational ocean models.

¹⁴ <https://eurosea.eu/deliverables/>

7. Conclusion

The EuroSea project has achieved many things towards an improved ocean observing and forecasting system during its four years of activities. This is mirrored and documented in many deliverable reports, scientific publications and outreach material. The impact in about 100 areas is also documented on the EuroSea website¹⁵. Nevertheless, and despite progress during recent years, also recognizing activities not funded or supported by EuroSea, the ocean observing and forecasting system still has many areas that need to be improved to reach “a user-focused, truly interdisciplinary, and responsive European Ocean Observing and Forecasting System, that delivers the essential information needed for human wellbeing and safety, sustainable development and blue economy in a changing world” – the articulated vision of EuroSea.

This report paints in broad strokes some of the needs along the ocean observing value chain. It is not a complete picture but represents a view from the coordinator based on 4 years of work within the consortium. For more details on progress of EuroSea, we refer to the numerous deliverables and scientific publications that represent the outcome of the project. Also, very important are the tangible results in form of services and products that the three demonstrator work packages produced for the societal benefit areas of ocean health, operational services and climate. Those results demonstrate outcomes and impacts for stakeholders when the ocean observing value chain is in operation. The vision of EuroSea is to expand on those results and disseminate those products to other partners and geographical areas, and that these can serve as an inspiration for the ocean observing and forecasting community to keep engaging with both the stakeholders, users and implementers of the system to improve ocean information services and products, for the benefit of society, the blue economy and science.

¹⁵ <https://eurosea.eu/>