EuroGOOS
European Global Ocean Observing System

AFFORDABLE TECHNOLOGIES FOR MARINE OBSERVATION

Low-Cost and Cost-Effective Approaches

EuroGOOS White Paper

This white paper was developed within the EuroGOOS Science Advisory Working Group and approved by the EuroGOOS Member Organisations.

Lead author Marco Marcelli

Co-authors Emilie Brévière, Lucie Cocquempot, Dina Eparkhina, Patrick Gorringe, Andrew King, Pablo Lorente, Michela Martinelli, Klas Ove Möller, Sara Morucci, Manolis Ntoumas, Michael Oellermann, Begoña Pérez-Gómez, George Petihakis, A Miguel Piecho-Santos, Viviana Piermattei, Jean-François Rolin, Stefania Sparnocchia, Filippo Tagliacarne, Riccardo Valentini, Manuel Ruiz Villarreal, Henning Wehde, Karen Wiltshire

External Reviewer Aldo Drago

Publication editor Dina Eparkhina

Graphic design Agata Smok

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Executive Summary

Context and Rationale

The health of the ocean is under unprecedented stress. Climate change, biodiversity loss, pollution, and human-driven pressures threaten marine ecosystems, coastal infrastructure, and the communities that depend on them. These cumulative changes have profound consequences for food security, economic stability, disaster risk reduction, and global resilience, while undermining the ocean's capacity to regulate climate and provide essential ecosystem services. Accurate, sustained, and integrated ocean observations are critical for understanding these dynamics, informing decision-making and policy, and supporting adaptive and anticipatory management across sectors and borders.

Traditional observation systems, including research vessels, moorings, autonomous vehicles, and satellite missions, have produced transformative scientific insights and underpin essential services such as weather and ocean forecasting, maritime operations, search and rescue, climate modelling, and civil protection. Ocean observation also remains the cornerstone of research and innovation, as marine ecosystems are still among the least explored natural habitats on Earth. However, the high capital and operational costs of many observing systems, together with limited spatial coverage and reliance on sustained investment from a small number of countries, restrict access to crucial data. This imbalance perpetuates knowledge gaps, particularly in the Global South and in under-sampled coastal and nearshore zones where pressures are high and many of the world's populations reside.

Low-cost and cost-effective technologies, including sensors, platforms, data transmission systems, and community-based monitoring tools, are emerging as transformative solutions. By reducing financial, technical, and operational barriers, these innovations expand the reach of oceanographic observation, enabling broader participation, more inclusive data collection, and greater resilience to environmental change, while supporting capacity building at local and regional scales. In doing so, they complement established observing systems, strengthen early warning and environmental monitoring capabilities, and contribute to a more inclusive and resilient ocean governance.

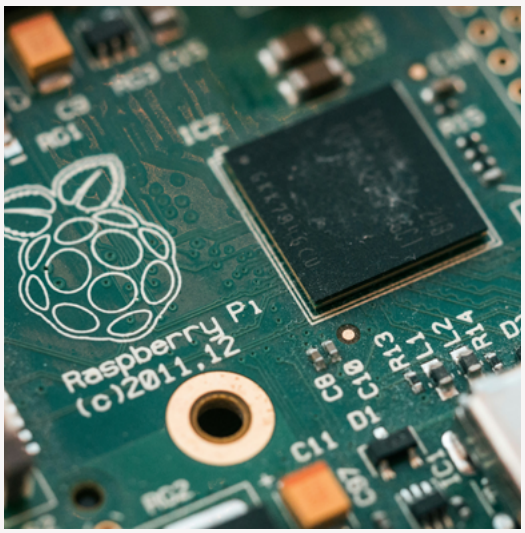
This white paper examines the state of the art, applications, benefits, limitations, and future directions of low-cost and cost-effective marine observation systems, alongside their role in enhancing the overall efficiency and sustainability of ocean observing networks. It outlines actionable recommendations for policymakers, researchers, and stakeholders, to support effective coordination and to advance the implementation of protection and restoration policies, aligned with the goals of the UN Decade of Ocean Science for Sustainable Development *(2021–2030)* and the Global Ocean Observing System *(GOOS)* 2030 Strategy.

Technological Landscape

Advances in Low-Cost Sensors

Affordable sensors have been developed for a range of Essential Ocean Variables *(EOVs)*, including temperature, salinity, dissolved oxygen, pH, turbidity, nutrients, and carbon dioxide. Emerging technologies also address marine acoustics, plankton imaging, animal-borne instruments, and environmental DNA *(eDNA)*. While some of these remain at early stages of development, advances in materials science, miniaturization, and open-source electronics *(e.g. Arduino, Raspberry Pi, ESP32)* have enabled the creation of increasingly accurate, modular, and accessible instruments.

The paper provides an in-depth state-of-the-art review of the recent technical advances in sensors for temperature, salinity, turbidity, chlorophyll-a and optical properties, dissolved oxygen, nutrients, pH and pCO_2, passive acoustics, plankton, sea level, waves, currents, animal-borne sensors, and eDNA samplers, highlighting their performance, maturity, and potential integration into sustained observing systems.



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Platforms and Observing Systems

Low-cost observing platforms range from miniaturized autonomous surface and underwater vehicles to open-source drifters, benthic landers, and modular buoys. Community-developed systems, often costing under USD 5,000, complement traditional high-end technologies by providing affordable redundancy, increased spatial coverage, and greater deployment flexibility. In addition, fishing vessels, ferries, and recreational boats equipped with sensors represent another cost-effective pathway to expand observations by leveraging existing maritime activities and infrastructure.

Data Transmission and the Coastal Ocean of Things

Wireless communication networks *(e.g. e.g. LoRaWAN, NB-IoT, LTE-M)*, satellite systems, and hybrid solutions are extending the reach of distributed observing systems. The concept of the Coastal Ocean of Things *(COOT)* envisions dense sensor networks connected via Internet of Things *(IoT)* protocols and supported by edge computing and cloud-based platforms, enabling near-real-time data transmission, processing, and analysis.

Artificial Intelligence and Machine Learning

Artificial Intelligence *(AI)* and Machine Learning *(ML)* tools are increasingly essential for calibrating sensor calibration, data validation, anomaly detection, and the enhancement of forecasting and modelling capabilities. These approaches support the scalable integration of heterogeneous datasets originating from satellites, in situ instruments, and community-based observations.

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Applications of Low-Cost Technologies

Low-cost tools are expanding the scope of marine science, operational oceanography, and resource management across a wide range of application domains:

- **Coastal Monitoring:** Affordable sensors enable the tracking of erosion, sediment transport, shoreline retreat, and flooding risks, supporting evidence-based adaptation strategies such as living shorelines, nature-based solutions, and managed retreat.
- **Open Ocean:** Programmes such as the Voluntary Observing Ship *(VOS)* and Ship of Opportunity Programme *(SOOP)* demonstrate the value of low-cost instrumentation for large-scale, long-term climate and weather observations, by leveraging existing commercial shipping activities.
- **Deep Sea:** Animal-borne sensors and pressure-tolerant technologies extend observations into deep and remote environments that have historically been inaccessible.
- **Environmental Monitoring and Conservation:** Low-cost technologies support the monitoring and management of Marine Protected Areas *(MPAs)* through biodiversity assessments, underwater noise monitoring, and the detection of pollution and environmental pressures.
- **Fisheries and Aquaculture:** Sensor-equipped fishing fleets contribute valuable environmental data, while aquaculture operators deploy low-cost sensors to monitor dissolved oxygen, nutrients, and water quality, reducing disease risk and improving operational efficiency.
- **Climate Change Research:** Affordable instruments enable the monitoring of ocean acidification, marine heatwaves, and deoxygenation, contributing critical observations to global databases, climate services, and Earth system models.

By enabling community-based monitoring and Citizen Science, these applications not only improve spatial and temporal coverage but also build local ownership, enhance Ocean Literacy, and facilitate the integration of traditional knowledge into regional and global observing frameworks.

The crumbling sandy cliffs of the south coast ©Nigel Freeman

Benefits and Advantages

This white paper highlights several transformative benefits of adopting low-cost marine observation technologies:

- **Cost-effectiveness and scalability:** Affordable devices lower entry barriers and enable broad deployment across diverse geographic, economic, and institutional contexts.
- **Expanded spatial and temporal coverage:** Distributed sensor networks help address persistent data gaps in coastal zones, under-sampled regions, the Global South, and hard-to-access environments, including the deep ocean.
- **Citizen Science empowerment:** By equipping communities with accessible tools, low-cost systems support the democratisation of science, expand environmental data coverage, strengthen environmental stewardship, and complement formal monitoring programmes.
- **Improved data accessibility and open science:** Open-source systems and open-access databases facilitate transparency, collaboration, and evidence-based decision-making.
- **Support to operational oceanography:** Enhanced availability of near-real-time data improves forecasting, early warning, disaster preparedness, and adaptive management across multiple sectors.

Challenges and Limitations

Despite their significant potential, low-cost systems face several technical, operational, and governance-related challenges:

- **Calibration and accuracy:** Many low-cost devices require rigorous laboratory calibration, validation, and intercomparison with reference instruments to ensure data quality and reliability.
- **Durability in harsh environments:** Corrosion, biofouling, and exposure to extreme conditions can reduce sensor longevity and performance.
- **Data transmission constraints:** Observations from remote and off-shore regions require energy-efficient and reliable connectivity solutions.
- **Standardisation and integration:** Lack of common standards, protocols, and certification pathways can hinder interoperability with established national, regional, and global observing frameworks.
- **Fitness-for-purpose:** Technologies must be adapted to local contexts, prioritising appropriateness and usability over one-size-fits-all solutions.

Addressing these challenges will require coordinated international efforts, sustained investment in research and development, and clear governance mechanisms for standardisation, quality assurance, and long-term integration.

Future Trends and Innovations

Looking ahead, several technological and societal trends are expected to shape the next generation of ocean observing systems:

- **Emerging technologies**: Advances in biosensors, nanotechnology, and novel materials promise more durable, sensitive, and energy-efficient observing devices.
- **Artificial intelligence**: Machine Learning-based automation will increasingly support calibration, quality control, anomaly detection, and large-scale data analysis.
- **Connectivity**: Advances in IoT, 5G, LoRa-to-satellite, and hybrid communication networks will enable seamless and global data transmission.
- **Global observing systems**: The expansion of GOOS, Argo, and regional observing systems will increasingly rely on low-cost and cost-effective technologies to fill observation gaps, particularly in underrepresented regions.
- **Societal engagement**: Low-cost technologies will continue to enable Citizen Science, education, and Ocean Literacy, reinforcing societal engagement and support for marine conservation and sustainable development.

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Recommendations and Call to Action

This white paper calls for the strategic integration of low-cost and cost-effective technologies as a core component of modern ocean observing systems. Key recommendations include:

- **Invest in research and development** to improve sensor accuracy, robustness, interoperability, and long-term reliability;
- **Support open-source hardware and open science platforms**, fostering collaboration, transparency, and wider uptake across regions and sectors;
- **Adapt policy frameworks, funding mechanisms, and procurement rules** to enable the adoption and scaling of affordable technologies;
- **Strengthen multi-stakeholder collaboration**, bringing together governments, academia, industry, and local communities;
- **Integrate Citizen Science and community-based monitoring** into global and regional frameworks, supported by sustained funding, training, and quality assurance mechanisms;
- **Expand education and capacity building**, equipping the next generation of practitioners and empowering resource-limited regions to contribute to and benefit from ocean observation;
- **Strengthen ocean and data literacy**, linking observation technologies, data use, and decision-making processes, and reinforcing public understanding, trust, and long-term support for sustained ocean observation.

By implementing these recommendations, stakeholders can co-create a more equitable, inclusive, and sustainable global ocean observing system, supporting science, policy, and societal needs.

Low-cost technologies are not merely less expensive alternatives to traditional instruments. They represent a paradigm shift toward more **democratised, scalable, and resilient marine science**. By expanding observational coverage, enabling broader participation, empowering communities, and fostering technological and social innovation, these technologies provide essential tools for addressing the urgent challenges of climate change, biodiversity loss, and sustainable resource management.

The effective integration of low cost and cost-effective technologies into global frameworks such as GOOS and the UN Ocean Decade initiatives will be critical to ensuring that ocean observation is not only scientifically robust, but also socially inclusive and globally accessible.

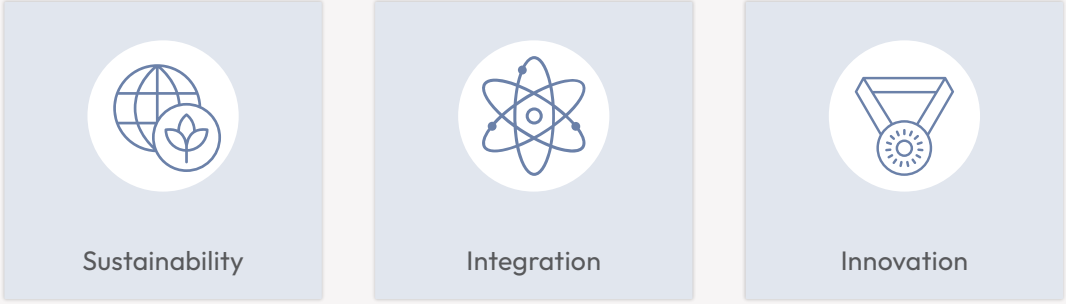
Together, these innovations lay the foundation for a **sustained, equitable, and resilient ocean observing system** capable of safeguarding marine ecosystems and the human societies that depend on them.

1. Introduction

The combined effects of climate change and anthropogenic pressures pose significant threats to marine ecosystems, coastal human activities, and infrastructures, with profound implications for health and safety, economies, marine biodiversity, and habitat integrity.

Sustaining ocean-based economic activities, advancing knowledge and forecasting, and supporting climate research are therefore recognised as strategic priorities within major international frameworks, including those led by the World Meteorological Organisation *(WMO)*, the United Nations Decade of Ocean Science for Sustainable Development *(2021-2030)*, and the G7 Future of the Seas and Oceans Initiative. Central to these efforts is the development of a sustained, multidisciplinary and integrated ocean observing system capable of delivering reliable, long-term information across spatial and temporal scales.

Integrated ocean observing systems are designed to provide critical information to scientists, stakeholders, and end-users, including by feeding observations directly into numerical models to improve forecasts and decision-support tools. However, their long-term sustainability increasingly depends on the development and deployment of low-cost and cost-effective technologies to enhance observing capabilities while reducing operational costs and addressing persistent observational gaps, particularly in ocean biogeochemistry and biology *(Wang et al., 2019, Marcelli et al., 2021)*. This approach directly contributes to the objective of a **"more environmentally sustainable ocean observing system"** as recommended by the Challenge 7, Sustainably Expand the Global Ocean Observing System, of the UN Ocean Decade Vision *(Miloslavich et al., 2024)*.



Within the UN Ocean Decade, the CoastPredict Programme[1], endorsed as a UN Ocean Decade Action and co-designed with GOOS, has emphasized the importance of expanding the use of low-cost sensors to enhance observational capacity in under-sampled coastal areas, particularly in the Global South. For this reason, low-cost technologies constitute a key component of GlobalCoast, the CoastPredict Framework for Implementation[2].

At the European level, the community has been particularly active in promoting both low-cost and cost-effective solutions, including approaches sometimes referred to as **"low tech"** *(terminology still evolving)*. These efforts are reflected in numerous European Union projects *(e.g. LandSeaLot, CS-MACH1, NAUTILOS, OPENMODS)* as well as in a growing body of reference literature *(Butler and Pagniello, 2021; Pieri et al., 2021; Možek et al., 2024;)*. EuroGOOS, the European Global Ocean Observing System, representing operational oceanography and observing community, plays a coordinating role through its regional systems *(ROOS)*, thematic working groups, and task teams. In March 2024, the EuroGOOS Technology Plan Working Group co-organized a dedicated event at Oceanology International entitled ***"Catching the momentum in ocean observing technology: optimizing value and data provision"***, which brought together a wide range of stakeholders and demonstrated strong community interest in low-cost technologies. Building on this momentum, the EuroGOOS Scientific Advisory Working Group organised a focused webinar on low-cost technologies. Following the success of this initiative, the concept of the present white paper was developed.

1 www.coastpredict.org
2 www.coastpredict.org/globalcoast

The ambition of the white paper is to support the uptake of low-cost and cost-effective technologies for the implementation of sustainable coastal and regional ocean observing systems. Aligned with both GOOS 2030 and EuroGOOS 2030 Strategies, the paper focuses on the following key aspects:

- **Low-cost sensors:** The integration of new physical, biogeochemical, and biological low-cost sensors into existing observing systems is essential to enhance coastal monitoring capabilities, improve spatial and temporal resolution, and address current observational limitations in a cost-efficient manner.
- **Reliability of low-cost sensors:** Low-cost sensors must achieve levels of precision, stability, and reliability to ensure their integration into consolidated observing systems and their appropriate use in applications such as community-based monitoring and Citizen Science.
- **Best practices and quality control:** Laboratory calibration, field validation, and intercomparison with established reference instruments are required. The development of best-practice protocols, standards, and minimum performance requirements, tailored to specific applications and aligned with existing global frameworks, remains a priority. These standards should address the temporal and spatial scales of application and ensure robust data quality control.
- **Low-cost and secure data transmission systems:** The cost of secure data transmission poses a limitation to the expansion of long-term observation systems, particularly for IoT-enabled platforms and cloud-based data access. The expansion of LoRaWAN networks and the availability of diverse satellite communication solutions offer opportunities to address these constrains.
- **Cost-effective observing platforms:** Enhancing observational capabilities across spatial and temporal scales, particularly for coastal systems, requires the development and deployment of autonomous platforms optimised for operational efficiency and long-term sustainability.
- **Artificial intelligence and machine-learning:** Machine learning and appropriately validated artificial intelligence techniques should be applied to data quality assessment, integration, and operational oceanography to support scalable and efficient use of heterogeneous datasets.
- **Low-tech and open-source approaches:** Wider adoption of low-tech and open-source technologies can further reduce barriers to participation, foster innovation, and support capacity building, particularly in resource-limited contexts.

1.1. Purpose and Scope

This white paper explores the transformative potential of low-cost sensors, technologies, and new platforms in advancing coastal and oceanographic observations. Coastal and marine environments are fundamental to the Earth's climate regulation, biodiversity conservation, and socio-economic sustainability. These regions provide critical ecosystem services, including carbon sequestration, nutrient cycling, and fishery resources, while also supporting cultural and recreational values. Although this white paper focuses primarily on coastal observing systems, it should be noted that some technologies, particularly cost-effective ones, are also used in open-ocean or deep-sea environments, and th4at the development of low-cost technologies can be extended beyond coastal observing systems to other domains.

Traditional observation systems, although sophisticated, are often constrained by high operational costs, limited accessibility, and regional disparities in deployment, and consequently, coverage. By addressing these limitations, this document emphasizes the pivotal role of affordable technologies in democratising data collection and enabling broader international and societal participation in marine science and environmental monitoring, thereby enhancing our capacity to address global challenges such as climate change, biodiversity loss, and marine resource management.

The scope of this white paper spans technological innovation, practical implementation, and interdisciplinary collaboration. It aims to serve as a resource for researchers, policymakers, and educators, and may be used by stakeholders as a guidance document. It advocates a shift toward inclusive, scalable, and cost-effective marine observation strategies aligned with global sustainability goals.
Finally, this white paper aims to contribute to the establishment of a dedicated activity focused on GOOS Essential Ocean Variables *(EOVs)*[3] for coastal observing systems - an issue critical to advancing the understanding and management of coastal environments and requiring precise and standardised monitoring frameworks.

3 www.goosocean.org/eov

Figure 1: **Framework Processes and Readiness Levels.** Requirements, observations, datasets and information products progress through defined readiness levels. Each component undergoes rigorous community review before attaining the highest level of readiness. This process actively promotes innovation while ensuring the coherence, quality, and reliability of the observing system, preventing the adoption of inadequate or insufficiently validated components.

	Requirements	Observations	Data & Information
Mature	Measurement validated through peer review, implemented at regional and/or global scales and capable of being sustained.	Following validation of observation via peer review of specifications and documentation, system is in Data model is articulated, expert review of interoperablity strategy. Verification of model with place globally and indefinitely.	Validation of data policy via routinely available and relevant information products.
Pilot	Measurement and sampling strategy verified at sea. Autonomous deployment in an operational environment.	Establishment of international governance mechanism, international commitments, and sustaining components Maintenance and servicing logistics negotiated.	Data management Practices determined and tested for quality and accuracy throughout the system. Creation of draft data policy.
Concept	Need for information identified and characteristics determined. Feasiblity study of measurement strategy and technology.	The system is articulated, capability is documented and tested. Proof of concept validated by a basin scale feasibility test.	Data model is articulated, expert review of interoperabilty strategy. Verification of model with actual observational unit.

Lowest Readiness Level

Framework Processes and Readiness Levels
Requirements, Observations, and Data & Information products move through readiness levels within the Framework. Each component will experience rigorous review, vetting, and approval by the community before reaching the highest level of readiness. This process will allow for innovation while protecting the system from inadequate or duplicative solutions.

The proposed activity would prioritize identifying and refining EOVs most relevant to coastal processes, ensuring that they address the specific physical, chemical, and biological characteristics of nearshore environments. In addition, the team would develop a detailed proposal to define a subset of EOVs tailored to low-cost coastal sea monitoring technologies, including applications in Citizen Science, thereby enabling broader and more equitable participation in global monitoring efforts.

By leveraging advances in affordable sensors, automated platforms, and data integration, this initiative would strengthen capacity for robust, high-resolution coastal ocean monitoring, providing essential data to support ecosystem management, disaster risk reduction, and sustainable development goals.

Coastal flooding ©Ariel Cattai, Unsplash

1.2. Key Needs and Requirements to Enhance Coastal Ocean Observations

Coastal regions are at the frontline of global environmental and socio-economic dynamics. These areas host diverse habitats such as coral reefs, mangroves, mudflats, and salt marshes, which are crucial for biodiversity and provide natural protection against climate-induced threats like storm surges and sea-level rise. Coastal ecosystems also support livelihoods by providing fisheries, tourism opportunities, and ecosystem services that underpin local and global economies.

Despite their significance, existing observation systems often fail to capture the complexity of these highly dynamic environments due to limited spatial and temporal resolution. Current systems remain constrained by high costs, technological barriers, and a strong reliance on traditional tools, which are often inaccessible to underfunded regions. Globally, there is a persistent bias in coastal and shelf sea observations toward well-resourced countries.

Key requirements for enhancing coastal observations include:

- **Development of flexible, scalable, low-cost technologies** to fill data gaps in under-monitored regions. For example, deploying low-cost unmanned surface vehicles *(USVs)* equipped with modular sensors can support the monitoring of critical parameters such as turbidity, nutrient fluxes, and pollutant dispersion in hard-to-reach coastal areas.
- **Integration of multi-disciplinary approaches** to address interconnected ecological, chemical, and physical processes. Coastal systems are shaped by strong land-sea interactions, requiring coordinated efforts among oceanographers, geologists, ecologists, and social scientists to design comprehensive monitoring frameworks.
- **Collaboration between local communities, governments, and international organisations** to foster capacity building and knowledge sharing. Engaging local communities helps ensure that observing networks align with regional socio-economic priorities and promote ownership of data-informed environmental management strategies.
- **Citizen Science** plays an increasingly important role in coastal observing by engaging local communities in data collection, observation, and analysis, thereby enhancing spatial and temporal coverage at relatively low cost. This participatory approach fosters public awareness and stewardship of coastal environments while complementing scientific datasets with valuable on-the-ground insights. Closely related, Community Science emphasises collective, place-based efforts to address specific environmental challenges through the co-creation of knowledge between scientists and community members. Together, these approaches contribute to the democratisation of science, empower communities, and strengthen the integration of local knowledge with scientific research to support effective coastal management and conservation.

Figure 2: Low-cost and cost-effective observing technologies in different marine and coastal environments

Enhanced coastal observation networks have the potential to significantly support responses to challenges *(Crise et al., 2018)*, including adaptation to sea-level rise, biodiversity conservation, and sustainable fisheries management.

By improving disaster preparedness through near-real-time monitoring and predictive modeling, these networks can help reduce the socio-economic impacts of extreme events such as hurricanes, storm surges, floods, and tsunamis *(Ahmed et al., 2023)*.

Cost-effective automatic temperature and depth profiling Sensors. ©OceanObserve-TZ

1.3. The Need for Marine Low-Cost Technologies

Traditional oceanographic tools, while sophisticated, are often financially and logistically prohibitive for widespread deployment, particularly in developing economies and remote regions. These constraints result in significant data gaps, hindering the capacity to address pressing environmental challenges effectively. Low-cost technologies offer a transformative opportunity by reducing operational barriers, enabling distributed observing networks, and helping to bridge critical gaps in global marine monitoring.

The need for low-cost technologies in ocean observing systems is driven by the urgency to expand global ocean monitoring coverage while overcoming financial and logistical constraints *(Marcelli et al. 2021)*. Traditional oceanographic instruments, such as autonomous underwater vehicles *(AUVs)*, research vessels, moorings and deep-sea sensors, are often prohibitively expensive, limiting their deployment to well-funded institutions and restricting long-term, large-scale data collection.

©Molly the Cat, Unsplash

Low-cost, open-source technologies offer an innovative solution by enabling the development of modular, scalable, and easily deployable monitoring systems. Affordable embedded systems, such as Arduino, ESP32, and Raspberry Pi, combined with miniaturised, high-precision sensors, allow for continuous real-time measurements of critical parameters like temperature, salinity, pH, and dissolved oxygen. These advancements make it possible to establish extensive sensor networks, autonomous surface and underwater platforms, and Citizen Science initiatives, significantly enhancing ocean data coverage.

The integration of low-power wireless communication and cloud-based data infrastructures further facilitates remote access and large-scale data sharing, supporting climate research, marine biodiversity conservation, and disaster preparedness. By broadening access to ocean observations, low-cost technologies pave the way for more inclusive and collaborative marine science *(Butler et al. 2021)* and help address crucial gaps in our understanding of ocean dynamics and the impacts of climate change *(Mariani et al. 2021)*.

Low-cost technologies empower local stakeholders by enabling them to take active roles in monitoring and managing their environments. For example, fishers and their fishing vessels are valuable partners for data collection in shelf and coastal seas: sensors attached to the gear can collect water-column profiles during routine fishing operations *(Van Vranken et al., 2023)*. This cost-effective and scalable approach is expanding globally *(e.g. Penna et al., 2023; Jakoboski et al. 2024; Hirose et al., 2024; Lago et al., 2025)*. Owning to its potential to fill observational data gaps at scale and complement existing GOOS networks, the Fishing Vessel Ocean Observing Network *(FVON)* has recently been endorsed as a UN Ocean Decade Action and has been recognized as an emerging GOOS network[4].

Portable salinity and temperature sensors can be deployed by artisanal and commercial fishers to gather critical data that informs regional fisheries management and helps fill gaps in marine observation *(Martinelli et al., 2016; Blanco-Gómez et al., 2023)*. These tools allow for georeferenced near real-time data collection, supporting adaptive decision-making in regions heavily affected by environmental change. Recent European Union Horizon 2020 projects, including NAUTILOS[5] and OPENMODS, have supported the development of cost-effective sensors suitable for these applications, extending observations to additional EOVs such as dissolved oxygen and chlorophyll *(Martinelli et al., 2023; 2024)*.

Modular design of low-cost technologies allows for flexible and incremental upgrades *(Marcelli et al., 2014)*, enabling actors with limited resources to progressively enhance their observing capacities. Closely aligned with open technology principles, modularity facilitates the integration or replacement of electronic components, firmware, sensors, and data transmission systems without the need for complete system redesign. For example, a modular sensor system may initially measure temperature and salinity and later incorporate dissolved oxygen or chlorophyll fluorescence.

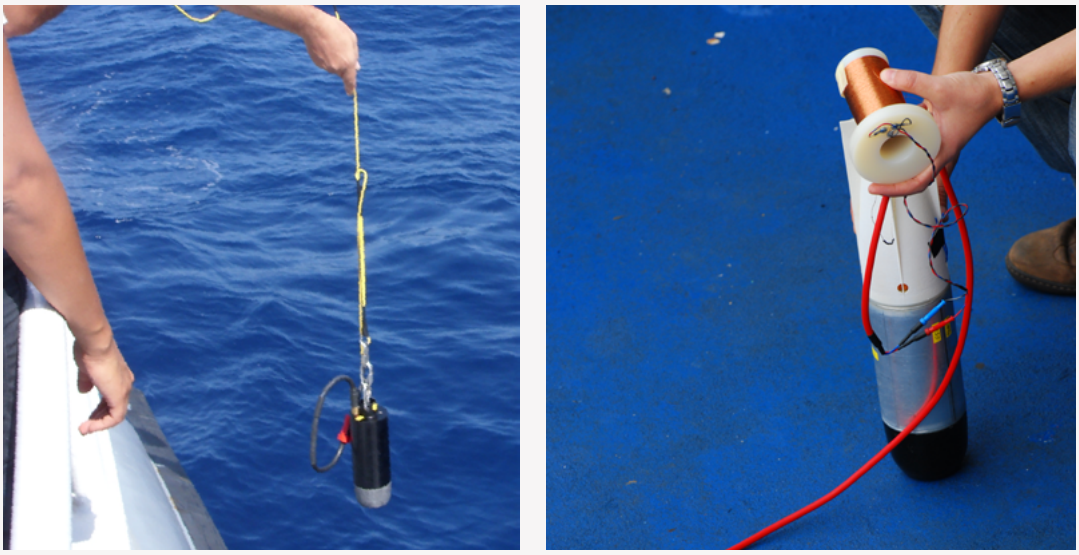
4 www.fvon.org
5 www.nautilos-h2020.eu

This adaptability allows resource-limited regions to access high-quality observational data without reliance on prohibitively expensive infrastructure *(Batubara et al., 2024)*.

The affordability and ease of deployment of low-cost technologies also make them suited for Citizen Science initiatives, in which community members actively contribute to data collection *(Bresnahan et al., 2022)*. This democratisation of marine science fosters inclusivity and ensures that the perspectives and needs of local communities are considered in broader environmental strategies, while fostering stewardship and public engagement in marine conservation *(Butler et al., 2021)*. Furthermore, low-cost technologies strengthen international collaboration by enabling data sharing and integration into global observing frameworks. Data from low-cost sensors are increasingly incorporated into GOOS components, including the Argo programme, while low-cost sea-level sensors for storm surges and tsunamis now contribute in near-real time to the Global Sea Level Observing System *(GLOSS)*. By broadening access to marine observations, these technologies help reduce disparities between regions and support more equitable participation in global ocean monitoring and conservation efforts *(Mariani et al., 2021)*.

Advances in low-cost technologies also facilitate the implementation of sensor and measurement redundancy, an essential requirement for the robustness and reliability of observing systems. Such systems must be capable of addressing varying spatial and temporal scales, supporting early warning services, and enhancing the performance of operational models.

Low-cost marine technologies are not merely cost-saving measures but **transformative enablers of equity, inclusivity, and collaboration in oceanographic research and resource management**. By lowering economic and logistical barriers, these technologies provide a critical pathway toward sustainable and effective marine governance at local, regional, and global scales.



Vertical Profiler and Expandable Probe Based on a Modular Architecture. ©Spectra Technology

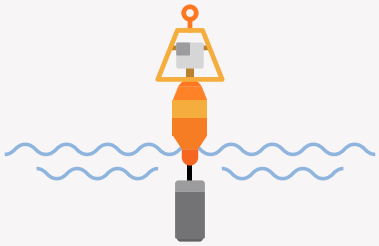
LOW-COST OCEAN SENSORS	COST-EFFECTIVE OCEAN SENSORS
	
Affordable *(minimizing upfront price)*	**Good value** *(with a high return of investment)*
Typical features: • Basic functionality • Accuracy and precision strictly connected to a rigorous laboratory calibration and field validation program • Limited calibration options: factory-calibrated and often lacking user calibration options • DIY-built hardware with compact size, open-source electronics and programming, and low power consumption	**Typical featured:** • Extended functionality • Higher accuracy and precision, stable measurements over time • Although factory calibrated, it allows user- performed field or laboratory calibration for optimal performance • Typically proprietary hardware and software, although they are occasionally open-source
Use cases: • Educational and citizen science projects • Prototyping and Proof of concept research • Large-scale or low-budget monitoring networks.	**Use cases:** • Long-term deployment • Extreme and remote environment applications

Figure 3: Summary of the main differences between low-cost and cost-effective ocean measurement technologies

While the terms ***"low-cost"*** and ***"cost-effective"*** are sometimes used interchangeably, they actually imply distinct concepts, particularly in the context of ocean sensors. This distinction is therefore clarified here.

Low-Cost Sensors: Characteristics, Limitations, and Applications

Low-cost sensors are designed to provide affordable and accessible alternatives to commercial instrumentation, making them particularly attractive for applications constrained by limited budgets. These sensors typically employ compact, do-it-yourself *(DIY)* hardware based on open-source electronics and programming platforms, enhancing their flexibility for prototyping, education, and exploratory use.

A key trade-off associated with their affordability is performance. The accuracy and precision of low-cost sensors are generally inferior to those of professional-grade instruments and are highly dependent on rigorous calibration and validation processes. Most low-cost sensors are factory-calibrated and often do not allow user calibration, limiting their adaptability across different environmental conditions. Consequently, when intended for scientific research or environmental monitoring, comprehensive laboratory calibration and in-field validation are essential to ensure data reliability.

From a technical perspective, these devices typically exhibit low power consumption and minimal maintenance requirements. However, they often have shorter operational lifespans due to the use of inexpensive materials with limited resistance to harsh environmental conditions. In many cases, they contain non-replaceable components, which further limits their long-term utility.

Low-cost sensors serve a variety of valuable purposes. They are widely used in educational settings and Citizen Science initiatives, where accessibility and ease of use are prioritized over precision. They are also instrumental in the development of prototypes and proof-of-concept experiments, as well as in the deployment of dense, low-budget monitoring networks, where high spatial resolution is prioritized over individual sensor performance.

Although not typically designed for high-accuracy applications, advances in sensor design and validation protocols have led to the development of some low-cost devices with performance levels suitable for scientific applications. In such cases, meticulous calibration and field-testing remain essential prerequisites for their effective use in research contexts.

Cost-Effective Sensors: A Strategic Balance Between Performance and Investment

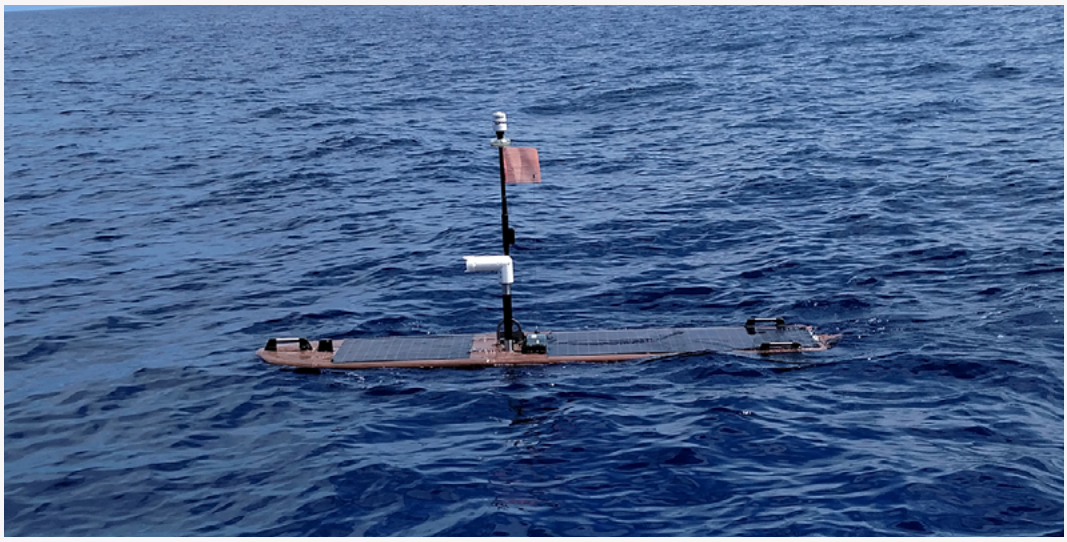
In professional, industrial, and research contexts, particularly within operational oceanography, the concept of cost-effectiveness has become increasingly important in sensor selection. Cost-effective sensors are defined not by their lowest initial price, but by their ability to deliver optimal long-term value through a favorable balance between performance and total cost of ownership *(TCO)*.

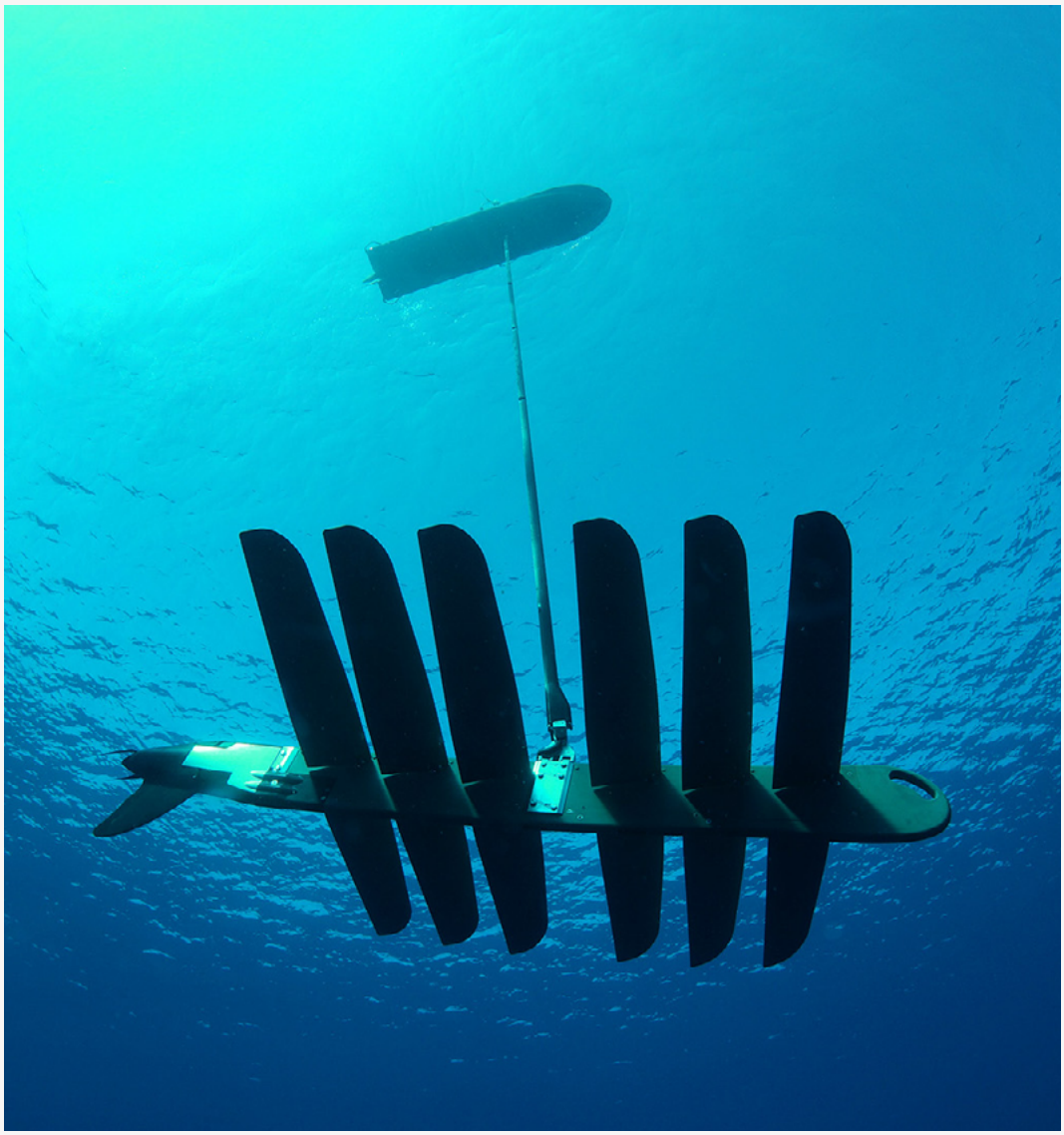
Unlike low-cost sensors, which may be appropriate for short-term or low-risk applications, cost-effective sensors are characterized by their capacity to deliver **high levels of accuracy, precision, and data stability over extended periods**. This reliability is essential in applications where consistent and trustworthy data are crucial. Although these sensors may involve higher initial investment, they typically result in lower operational costs over time due to greater durability, reduced maintenance requirements, and longer service life.

Key attributes of cost-effective sensors include factory calibration *(with options for user or field calibration as needed)*, robust construction using durable materials such as reinforced plastics or metal casings, and high-quality sensor elements engineered for long-term operation. These sensors are often energy-efficient, making them suitable for continuous deployment in remote or autonomous observing systems.

In addition, cost-effective sensors are designed to produce digital or analog outputs compatible with data management infrastructures and interoperable platforms such as SeaDataNet and Copernicus. This enhances their integration into larger monitoring networks, facilitating efficient data sharing and broader downstream applications.

As demand for accurate, stable, and sustainable environmental data continues to grow, the oceanographic community is **increasingly favouring cost-effective sensor technologies over purely inexpensive alternatives**. Their ability to combine robust performance with economic viability over the full lifecycle positions them as a strategic investment for long-term, high-quality ocean observation and monitoring.





Wave Glider ©Liquid Robotics

1.4. Key Challenges in Marine Observations

One of the key challenges in marine observation is achieving comprehensive spatial and temporal coverage of the vast and dynamic oceanic environment. The high costs and logistical complexity associated with deploying and maintaining observing platforms, such as research vessels, autonomous vehicles, and moored buoys, limit the density and continuity of data collection, particularly in remote or harsh environments like the polar regions and the deep ocean. However, the development of cost-effective technologies, particularly low-cost sensors, has emerged as a promising solution to improve the accessibility and sustainability of ocean monitoring efforts.

These technologies enable broader deployment of instruments across diverse platforms, including Citizen Science initiatives and small autonomous systems, thereby enhancing observational capabilities at reduced operational costs. Nonetheless, the integration of heterogeneous data sources *(e.g., satellite remote sensing, in situ measurements, and numerical models)* continues to pose technical challenges related to data standardisation, quality control, and interoperability. Climate change further increases the urgency and complexity of these challenges by driving the need for long-term, high-resolution datasets capable of capturing rapid environmental changes and their impacts on marine ecosystems. Addressing these issues requires international collaboration, sustained investment, technological innovation, and the continued development of robust, scalable, and affordable ocean observing systems globally.

The evolution of low-cost ocean observing systems represents a critical frontier for advancing marine science and operational monitoring. As technologies continue to mature, these systems are expected to transition from experimental tools to integral components of global observing networks. Their development addresses a wide range of challenges while offering significant opportunities for innovation and wider participation.

In coastal and nearshore areas, the deployment of affordable instruments can substantially enhance spatial coverage, improving the capacity to monitor rapidly changing environments such as estuaries, lagoons, and areas impacted by human activities. This increased resolution is essential for understanding coastal dynamics, supporting ecosystem management, and informing policy decisions in regions where human and natural systems closely interact.

In the open ocean, low-cost systems offer opportunities to expand observational coverage in regions that are traditionally undersampled due to high logistical and financial barriers. By leveraging advances in miniaturisation, autonomous platforms, and open-source designs, it becomes feasible to establish large-scale observing arrays at a fraction of the cost of conventional technologies, thereby contributing to the democratisation of ocean science.

Equally important is the application of these systems in extreme and harsh environments, such as during storms or in polar regions. The capacity to operate under such conditions not only broadens the scope of scientific inquiry but also ensures the resilience of observing networks in the face of climate change. Low-cost, robust solutions will be instrumental in capturing data where traditional systems are often impractical or unsustainable.

Taken together, the development of low-cost ocean observing systems marks a transformative step toward more inclusive, comprehensive, and resilient global monitoring capabilities. Their ongoing refinement and integration into operational frameworks will significantly strengthen our ability to address emerging scientific, societal, and environmental challenges.

1.5. Ambitions of the White Paper

The ambitions of this white paper are to:

- **Bridge the gap between innovation and implementation by providing a comprehensive overview of low-cost and cost-efficient technologies.** This includes detailed analyses of advances in sensor design, data transmission, and integration with existing systems, with emphasis on how these innovations address the specific challenges of coastal observations. Furthermore, a strengths–weaknesses–opportunities–threats *(SWOT)* analysis of sustainable low-cost ocean sensors has been performed *(Figure 1)* as a situational framework to assess the current status, benefits *(as described in Section 4)*, and future prospects of deploying such technologies for environmental monitoring and oceanographic research. The SWOT analysis also helps identify challenges and limitations *(further analysed in Section 5)* associated with implementation, supporting long-term strategic planning and informed decision-making.
- **Advocate for policy frameworks that incentivise the development, deployment, and maintenance of affordable observation systems.** This includes recommending targeted investments, fostering public-private partnerships, and implementing financial mechanisms to support research, infrastructure development, and system consolidation.
- **Highlight the role of open-access platforms and data-sharing mechanisms in promoting collaborative research.** Open science initiatives ensure that data generated by low-cost technologies are accessible to diverse stakeholders, including researchers, policymakers, and community actors, thereby fostering interdisciplinary collaboration and large-scale analyses critical to addressing global environmental challenges.

- **Provide actionable recommendations for integrating low-cost technologies into global and regional marine observation networks.** These include best practices for sensor deployment in challenging environments, capacity-building programmes for local stakeholders, and guidelines on data standardisation to ensure interoperability across global networks.
- **Strengthen Community Science is essential for enhancing the coastal ocean observing system by fostering stronger partnerships between local communities and scientific institutions.** This involves equipping communities with accessible tools, training, and resources to collect high-quality data on coastal conditions, such as water quality, biodiversity, and climate impacts. Strengthening Community Science not only improves data density and diversity but also ensures the inclusion of local knowledge, which is critical for addressing site-specific challenges. By integrating these efforts into broader observing networks, Community Science can significantly contribute to a more comprehensive, equitable, and resilient coastal monitoring system, empowering communities to actively participate in sustainable coastal management.

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

This white paper aims to inspire a paradigm shift in how coastal and oceanographic observations are approached. By leveraging low-cost technologies, it seeks to enhance data collection, promote equitable resource management, and build resilience in vulnerable coastal areas, in alignment with global sustainability goals and international environmental commitments, such as the United Nations Agenda 2030 and the Ocean Decade.

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2. Technological Landscape and State of the art

2.1. Overview of Marine and Oceanographic Observations

Marine observations are indispensable for understanding ocean dynamics, ecosystem resilience, and the impacts of anthropogenic activities. These observations have directly influenced critical policy decisions and scientific advancements. For instance, long-term data from marine observing systems have been pivotal in shaping international agreements such as the Paris Agreement by providing evidence of ocean heat uptake and its role in moderating global warming. Similarly, regional initiatives like the European Marine Strategy Framework Directive rely on comprehensive oceanographic data to establish Good Environmental Status (GES) benchmarks for marine ecosystems.

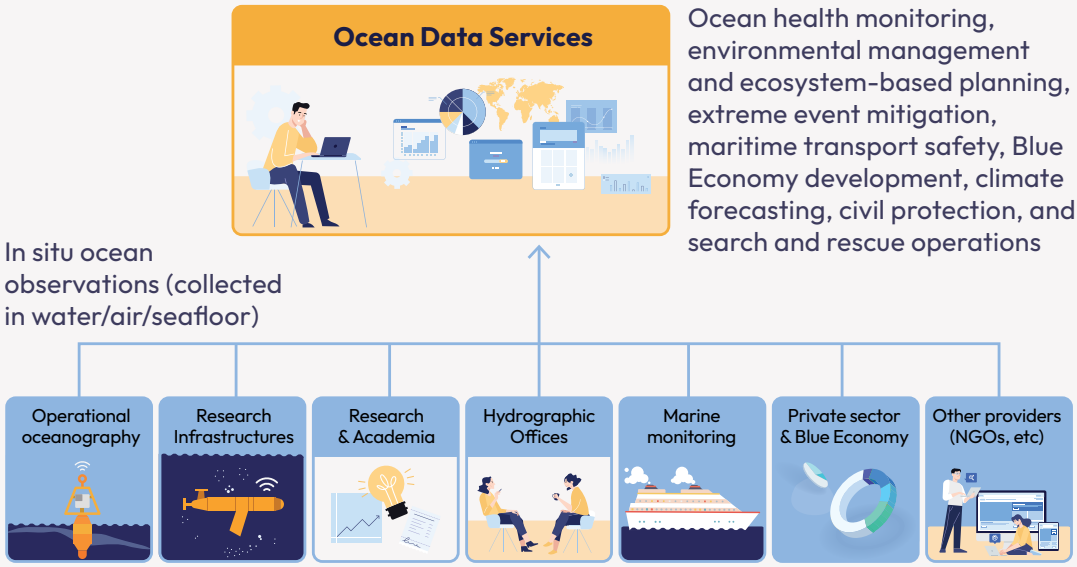


Figure 4: A non-exhaustive overview of data collection efforts and the services they support

On the scientific front, marine observations have enabled groundbreaking discoveries such as the global thermohaline circulation, often referred to as the *"ocean conveyor belt,"* which has profound implications for climate regulation and weather patterns. Observational data from the Southern Ocean, collected through programmes like Argo floats, have shed light on deep ocean carbon storage, influencing global carbon cycle models and informing strategies to mitigate climate change *(Roemmich et al. 2009)*. These examples underscore the critical role marine observations play in linking science to actionable policies and advancing our understanding of Earth's interconnected systems. These systems provide essential data for modelling ocean circulation, analyzing long-term variations, predicting climate phenomena, and monitoring marine biodiversity.

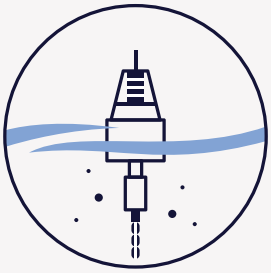
Key technologies in marine and oceanographic observations include:

Satellite remote sensing: Satellites equipped with advanced sensors measure a range of key parameters such as sea surface temperature, chlorophyll concentration, ocean currents, and sea level changes. A notable example is the Sentinel-3 mission, part of the European Space Agency's Copernicus programme, which provides high-resolution data on sea surface temperature and ocean colour, essential for climate monitoring and marine ecosystem studies. Similarly, NASA's Aqua satellite, with its Moderate Resolution Imaging Spectroradiometer *(MODIS)*, has revolutionized our ability to track phytoplankton blooms and assess global carbon cycles. These missions highlight how remote sensing underpins critical advancements in understanding ocean processes and addressing environmental challenges. They provide large-scale coverage but are limited in resolving fine-scale processes or subsurface dynamics.

Oceanographic Research Ships: These ships serve as mobile laboratories, enabling researchers to conduct comprehensive surveys and deploy equipment such as CTD *(Conductivity, Temperature, Depth)* rosettes and sediment corers. They are unique platforms for large multidisciplinary site assessments involving many instruments and for deploying long-term monitoring platforms *(see moorings, seafloor and water column fixed point observatories)*. They were unique for the training of ocean observation teams. Real-time connections are opening the way to remote interventions by specialists. They are nationally funded but, especially in the European Research Area, alliances such as Eurofleets are showing the way to more cooperation. High seas *(including polar capacities)* vessels, coastal regional ships, and coastal local ships have been described by the Eurofleets large research infrastructure. Notable examples include the RV Atlantis and the RV Polarstern, which have contributed to pivotal studies ranging from hydrothermal vent ecosystems to polar climate dynamics. These ships remain indispensable for gathering high-resolution data across wide geographic areas. They may be necessary for intercomparison of low cost and reference sensors.

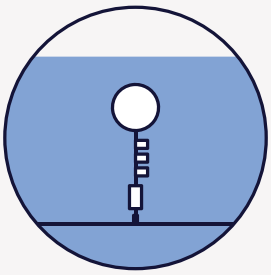
During transit legs *(repositioning transfers)*, **research ships, minor research vessels, and other vessels adapted for scientific activities** can serve as effective platforms for the use and deployment of low-cost or low-technology sensors. These operational phases provide valuable opportunities to test and deploy additional instruments beyond those included in the planned cruise instrumentation. This is particularly relevant in offshore waters, where the cost of sensor deployment is strongly influenced by the logistical challenges and expenses associated with accessing remote areas. By taking advantage of scheduled research vessel operations and transit periods, the overall cost of deploying sensors in offshore environments can be significantly reduced. Furthermore, additional opportunities are offered by auxiliary or privately operated vessels that allow occasional or opportunistic scientific activities, further enhancing spatial and temporal data coverage at relatively low cost.

Key technologies in marine and oceanographic observations include:

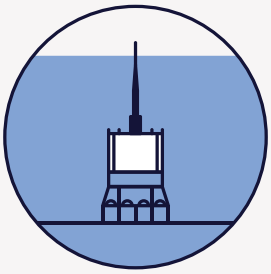


Fixed point observing systems: Fixed point or eulerian observatories are stationary with respect to their position on or above the seafloor *(Gonzales et al. 2025)* . These fixed platforms host different types of sensors for making a wide range of measurements at the surface, on the seabed or throughout the water column. Regardless of their position in the water, fixed platform measurements provide information at high vertical and temporal resolution from the atmospheric boundary layer, down through the ocean mixed layer, to the abyss, on time scales of minutes to years *(Cristini et al., 2016; Coppola et al., 2016)*. This capability gives fixed point observing systems a unique role in the global ocean observing network, providing an unparalleled ability to detect processes that research vessel cruises and daily satellite observations may miss.

Fixed point observing systems category includes:



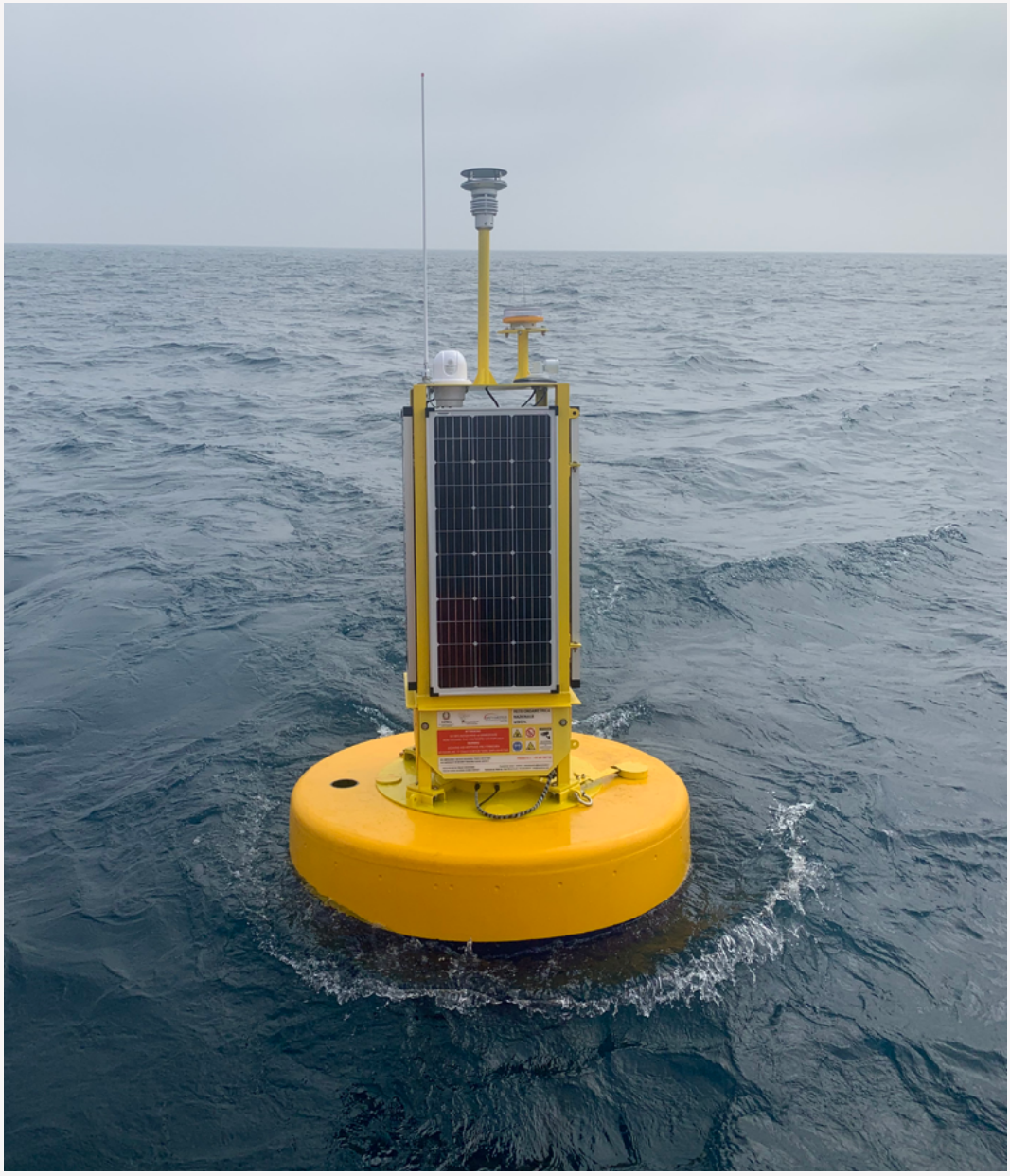
Subsurface moorings: Autonomous long-term observation stations that continuously collect measurements along the water column at key locations. They are a collection of devices and sensors connected to a wire and anchored on the seafloor. They help to identify and understand natural variations in the ocean as well as changes due to climate change and are essential for measuring Essential Ocean Variables. They are often used in networks with the other types of fixed measuring platforms.



Deep-Sea seafloor observatories: Fixed installations on the seafloor enable continuous monitoring of environmental variables, such as seismic activity, ocean chemistry, and benthic ecosystems. They can operate as standalone systems or as cabled systems connected to a shore station. Cabled observatories can be used both in coastal and deep water. They may also have also subsurface moorings deployed close by and connected to the cable to shore through a junction box *(Coppola et al., 2016)*. Notable examples include the NEPTUNE observatory off the Pacific coast of Canada, which provides real-time data on seismic activity and oceanographic conditions, significantly enhancing earthquake preparedness and tsunami research. Another example is the Hawaii Undersea Research Laboratory *(HURL)*, which has been instrumental in exploring deep-sea ecosystems and historical shipwrecks. These observatories serve as critical platforms for advancing scientific understanding of deep-sea environments and addressing global challenges such as climate change and marine biodiversity conservation. They produce long-term time series, but additional low-cost sensors in numbers are often valuable to increase their spatial coverage. Examples include the Ocean Networks Canada initiative and the European Multidisciplinary Seafloor and Water Column Observatory *(EMSO)*. It must be noted that both are increasingly including more coastal sites in their large multi-site infrastructures.

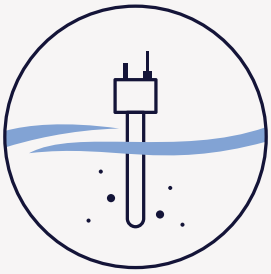
Fixed point observing systems category includes:

Moored Buoys: Fixed buoy systems are equipped with multiple sensors to measure variables such as waves, currents, temperature, salinity and a range of biogeochemical parameters over extended periods. The Tropical Atmosphere Ocean *(TAO)* array in the Pacific Ocean exemplifies the importance of moored buoys in monitoring El Niño-Southern Oscillation *(ENSO)* events, providing critical data for climate prediction models *(CIT)*. Complementarily, the global navigation satellite system *(GNSS)* wave buoys currently in use can accurately measure ocean surface waves at a high sampling rate *(Liu et al., 2022; Gu et al., 2023)*.

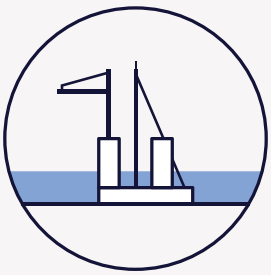


Fixed platform ©ISPRA

Key technologies in marine and oceanographic observations include:



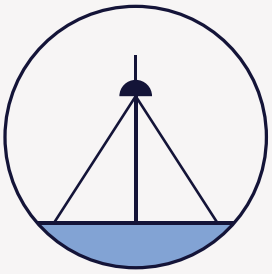
Argo: Autonomous profiling floats are a transformative technology for oceanography, enabling continuous, real-time subsurface observations of the global ocean and complementing satellite observations of the sea surface. The implementation of a global float array, named Argo to emphasize its synergy with the Jason satellite altimeter, began in 1999. Since then, steady advances in profiling float and sensor technologies have opened many exciting possibilities for Argo's future, including expanding sampling into high latitudes and the deep ocean, improving near-surface sampling, and adding biogeochemical parameters *(Roemmich et al., 2009)*. The Bio-Argo programme is an extension of the Argo global ocean observation system, designed to enhance the understanding of the ocean's role in the Earth's climate and ecosystems by incorporating biogeochemical sensors on autonomous profiling floats that monitor key parameters such as dissolved oxygen, pH, chlorophyll or nitrate *(McKee et al., 2023)*. The Lagrangian floats of the Argo projects were developed initially thanks to the integration of hydraulic components from the truck industry *(Ollitrault et al.,1995)*. As a reuse practice, this may be an option for innovative design of low-cost instruments.



Tide gauges: Essential platforms for monitoring sea level changes along coastlines, one of the Essential Ocean Variables *(EOVs)* most affected by climate change and with significant impacts on coastal areas and national economies. Nationally funded networks of tide gauges, typically located in ports and harbors, have operated for decades to serve applications such as tidal predictions, vertical datum definitions, coastal infrastructure design, and port operations *(Quijano de Benito et al. 2022)*. Since 1985, the Global Sea Level Observing System *(GLOSS)* has provided oversight and coordination to maintain a well-structured, high-quality sea level observing network that supports both research and operational use across various temporal and spatial scales *(IOC/UNESCO, 2012)*. Built around the GLOSS Core Network - 290 stations in over 90 countries and territories to ensure global coverage - today more than 2000 tide gauges contribute to GLOSS portals. Before satellite altimetry, tide gauge records were the main source of information on long-term global sea level trends and remain fundamental for understanding local sea level rise and extremes *(Woodworth and Player, 2003; Holgate et al., 2013; Oppenheimer et al., 2019)*. They have also played a key role in major assessments, including those by the Intergovernmental Panel on Climate Change *(IPCC)*. This long-established network has continually evolved, from early float-based gauges to modern acoustic and radar sensors and co-location with GNSS for vertical land motion estimation, expanding its role to include storm surge forecasting and tsunami alerts *(Pérez Gómez et al., 2022)*.

Key technologies in marine and oceanographic observations include:

Drifters: These are free-floating devices equipped with GPS/GNSS and sensors to measure surface currents, temperature, and salinity. Drifters contribute to real-time monitoring of ocean circulation patterns *(Poulain et al., 2013; Lumpkin et al., 2017)* and have been integral to studies of pollutant dispersion, including tracking the movement of oil spills and marine debris *(Novelli et al., 2020, Merlino et al. 2023b)*.

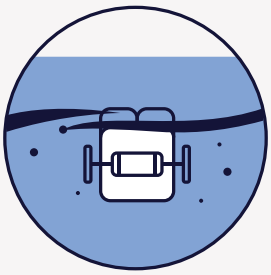


High-Frequency Radars (*HFR hereinafter*): This consolidated land-based remote sensing technology is based on measurements of the radio-wave backscattered signal from ocean surface gravity waves in the 3–30 MHz range of the electromagnetic spectrum *(Crombie, 1955)*. HFR can provide, in near-real time, fine-resolution maps of the surface circulation over broad coastal areas *(Janzen, 2019)*, along with reliable directional wave and wind information, thereby providing hence a dynamical framework for other observation platforms. It presents a broad range of practical applications, encompassing search and rescue operations, marine safety, oil spill emergencies, vessel tracking or water quality monitoring *(Roarty et al., 2019)*.

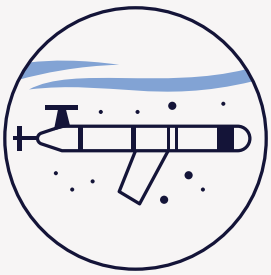
X-Band Radars: This technology is widely used in marine and coastal environments due to their high resolution and sensitivity to sea surface features. These radars are particularly effective for monitoring sea surface conditions, as they can capture short-scale wave patterns and surface roughness in great detail. In marine applications, X-Band Radar is commonly used to estimate wave parameters such as height, period, and direction, by analyzing the radar backscatter from the wave field.

They are also employed to derive surface currents and, with advanced processing, to retrieve shallow-water bathymetry. In coastal areas, X-band radar plays a crucial role in monitoring nearshore dynamics. It is used to observe wave transformation, breaking patterns, and sediment transport processes *(Serafino et al. 2021)*. This information is essential for coastal erosion studies, beach nourishment projects, harbor management, and early warning systems for storm surges and flooding. Its ability to provide continuous, real-time, and non-intrusive observations makes X-band radar a powerful tool for both scientific research and operational coastal monitoring.

Mobile platforms category includes:



Autonomous Underwater Vehicles (*AUVs*): These robotic platforms collect high-resolution data on oceanographic parameters such as salinity, temperature, and dissolved oxygen. AUVs have proven invaluable in diverse missions, such as exploring hydrothermal vents, where they navigate challenging deep-sea conditions to measure temperature and chemical gradients. For example, AUVs played a critical role in mapping the Deepwater Horizon oil spill, providing detailed data on the extent and trajectory of subsurface plumes *(Camilli et al., 2010; Kinsey et al., 2011)*. Their ability to operate autonomously under ice sheets has also advanced polar research, enabling studies of ice-ocean interactions critical to understanding climate change impacts. These unique capabilities make AUVs indispensable for both exploratory missions and routine monitoring in otherwise inaccessible environments. AUVs are particularly useful for exploring inaccessible or hazardous marine environments, including deep-sea ecosystems and under-ice regions.



Gliders: Underwater gliders are autonomous vehicles designed to collect oceanographic data over extended periods and distances. They are particularly useful for monitoring parameters such as temperature, salinity, and currents in regions where traditional ship-based observations are impractical. Gliders have been deployed to study seasonal changes in ocean dynamics and assess the impacts of hurricanes on coastal systems *(Schofield et al., 2007)*. Complementarily, bio-optical gliders are innovative devices that can be equipped with various sensors to monitor a wide range of environmental and biological parameters, depending on their design and purpose *(Kaufman et al., 2018)*;

Unmanned Surface Vessel (*USV*) or Autonomous Surface Vehicles *(ASV)*: Designed to collect data over long durations and wide areas without the need for constant human intervention. They can be equipped with a range of sensors to monitor the bathymetry and seafloor typology, sea surface temperature, salinity, currents, meteorological conditions, and even biogeochemical parameters. ASVs are particularly useful for real-time monitoring, coastal studies, and in areas difficult or dangerous for crewed vessels, enhancing our understanding of ocean processes with minimal environmental impact.

Despite their transformative capabilities, all these technologies are expensive, often requiring significant financial, technical, and logistical resources. Countries with emerging economies, in particular, face challenges such as limited access to funding, inadequate infrastructure, and a lack of technical expertise necessary for deploying and maintaining advanced marine observation systems. These barriers result in significant data gaps, impeding their ability to monitor critical marine ecosystems effectively and to respond to environmental crises.

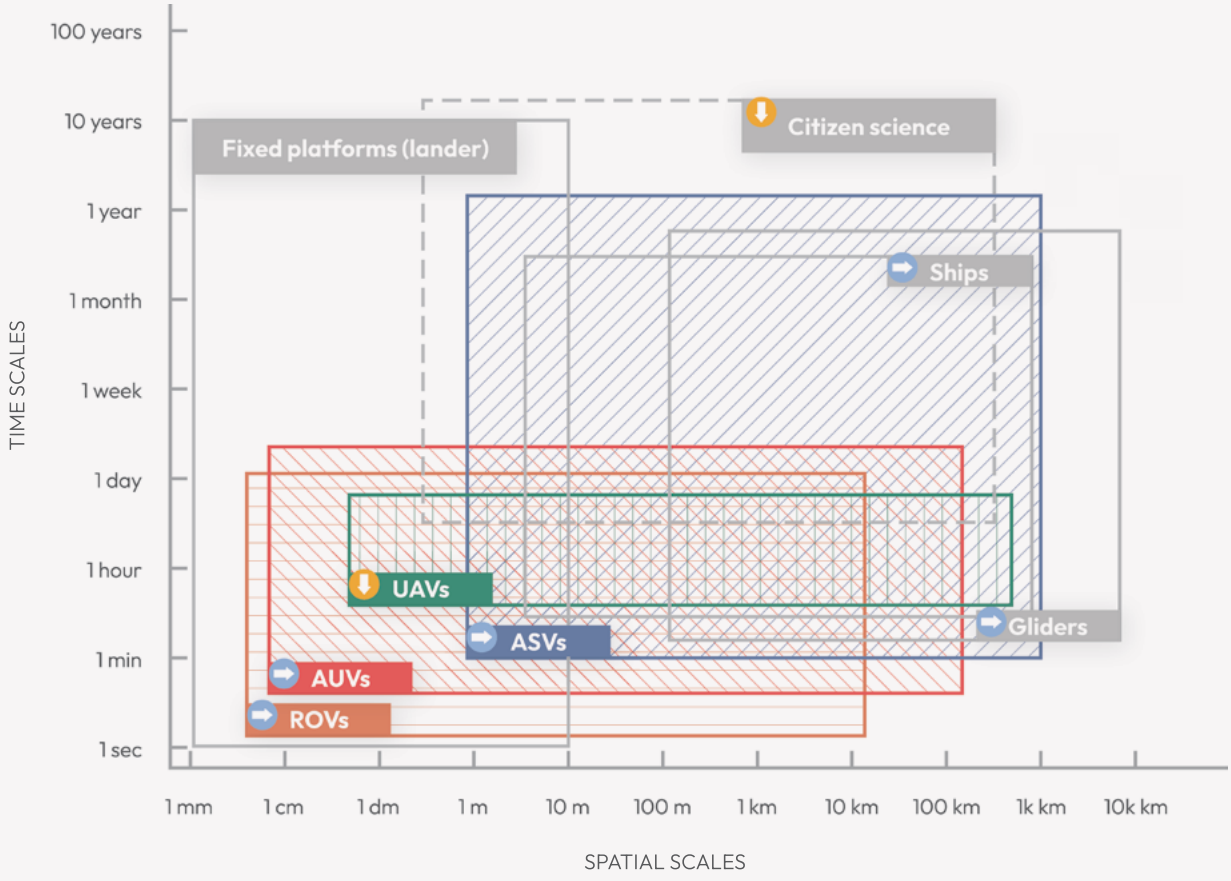


Figure 5: Spatial and temporal scales of various measurement platforms, highlighting the distinction between cost-effective and low-cost options. The lower end of the axis represents resolution, while the upper end represents maximum coverage. [ROV = Remotely Operated Vehicle; ASV = Autonomous Surface Vehicle (also called USV); UAV = Unmanned Aerial Vehicle; AUV = Autonomous Underwater Vehicle]. The cost-effective platforms include: ROV, ASV, Glider, Argo, AUV, and coastal ships of opportunity (fishing boats, coast guard vessels, etc.). The low-cost platforms include: moorings of opportunity, citizen science, UAVs, specific developments, and low-cost drifters. Adapted from Nornes, 2018.

Noise Monitoring

Anthropogenic noise pollution, mainly from commercial shipping, offshore industrial activity, and seismic exploration, has significantly altered marine acoustic environments *(Hildebrand, 2009)*. Marine noise is typically categorized into impulsive *(short, high-intensity)* and continuous *(persistent, low-frequency)* types, the latter largely linked to maritime traffic and machinery *(Richardson et al., 1997; Southall et al., 2007)*.

These sound sources adversely affect marine organisms, causing auditory damage, physiological stress, behavioral changes in communication, foraging, and migration, and even long-term impacts on reproduction and survival *(Popper & Hastings, 2009; Erbe et al., 2019)*. As sound is vital for key biological functions, such as navigation, predator avoidance, and social interaction, marine bioacoustics has become essential for understanding and mitigating these effects *(Tyack, 2008; Duarte et al., 2021)*. In response, the European Union's Marine Strategy Framework Directive *(2008)* established Descriptor 11, requiring Member States to monitor underwater noise. This includes assessing anthropogenic sound against natural ambient baselines, such as those from weather and biological sources, to manage and reduce acoustic impacts on marine ecosystems.

Low-cost alternatives address these issues by reducing financial barriers and simplifying operational requirements. For instance, affordable and user-friendly sensor systems enable local communities to participate in data collection, fostering capacity building and ensuring that critical regions are not excluded from global monitoring networks *(Palmer et al., 2021)*. Additionally, modular designs and scalable platforms allow for incremental upgrades, enabling nations with limited resources to progressively enhance their observational capabilities. By democratising access to essential data, low-cost technologies play a vital role in promoting equitable participation in marine science and supporting sustainable ocean governance worldwide *(Buck et al., 2019)*. Their deployment is predominantly concentrated in developed economies, leaving substantial data gaps in under-monitored regions, particularly in the Global South.

The evolution of low-cost sensors and observing platforms represents a paradigm shift in marine science. A paradigm shift, in this context, refers to a fundamental transformation in how marine observations are conducted, transitioning from reliance on expensive, high-maintenance technologies accessible primarily to well-funded institutions, to inclusive, scalable solutions that empower broader participation.

For instance, the widespread use of low-cost Argo floats has revolutionized global ocean temperature and salinity monitoring, enabling near-real-time data collection at a fraction of the cost of traditional ship-based surveys *(Rudnick et al., 2018; Riser et al., 2016)*. Similarly, initiatives like citizen-deployed sensors have democratised data collection, fostering community engagement and expanding the spatial coverage of observations *(Garcia-Soto et al., 2017; Kelly et al., 2020; Sandahl et al., 2020)*. These examples illustrate how low-cost technologies have redefined operational models in marine science, making critical data accessible to diverse stakeholders and advancing global efforts in ocean conservation and climate resilience. These advancements facilitate decentralized data collection, allowing for real-time monitoring and enhanced regional collaboration. For instance, low-cost weather buoys and community-deployed sensors have proven effective in regions with limited access to advanced infrastructure.

Additionally, these systems enable local stakeholders to actively participate in data collection and analysis, fostering capacity building and promoting equitable access to marine science.

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2.2. Advancements in Low-Cost Sensors and Technologies

The need for low-cost sensors and technologies in oceanographic and marine research is driven by the vastness and inaccessibility of the ocean, the high cost of traditional instruments, and the urgent demand for widespread, continuous, and high-resolution data to monitor environmental changes, marine ecosystems, and climate impacts. Affordable tools enable wider engagement, facilitate broad-scale observation networks, support developing economies, and enhance data coverage, ultimately advancing both scientific understanding and marine conservation efforts.

Over the past decade, open-source electronic platforms have transformed technology development, making hardware and software more accessible to both beginners and experts. Among these, Arduino[6] launched in 2003, remains the most widely used due to its open-source Integrated Development Environment *(IDE)* and the extensive global community that supports it.

This collaborative network of students, hobbyists, artists, programmers, and professionals has contributed to the development of thousands of projects, ranging from everyday smart devices to sophisticated scientific instruments.

The availability of affordable electronic components from small online suppliers has further facilitated the modular design of customized measurement systems.

Recent technological advancements now make it possible to develop low-cost, high-accuracy instruments with impressive capabilities. Embedded systems have become more powerful, widely available, and easy to programme, allowing for efficient control, data storage, and real-time processing. Microcontrollers such as ARM, Arduino and ESP32, along with embedded computers offer flexible programming environments, ranging from C, Python and MicroPython to full Linux-based systems. Furthermore, these microprocessors are continuously upgraded in terms of size and power consumption, becoming increasingly smaller and lower-power.

At the same time, integrated circuits originally designed for medical and industrial applications now provide cost-effective solutions for signal conditioning and analogue-to-digital conversion, achieving precision levels that were previously unattainable at low cost. The rapid development of miniaturised sensors has further expanded possibilities, making it easy to integrate compact spectrometers, environmental monitors, and multi-parameter analyzers into new instrumentation.

These advancements are revolutionizing scientific research and real-world applications, enabling the creation of sophisticated, scalable, and affordable measurement tools. With open-source technology and a global community of developers, the future of instrumentation is more accessible than ever.

6 www.arduino.cc

Sensors

Many low-cost instruments and sensors have been developed with varying characteristics in terms of measurement performance *(accuracy, sensitivity, and robustness)* and usability.

Some of these have been successfully deployed on buoys, autonomous surface vehicles *(ASVs)*, underwater gliders, and fixed installations, while others remain in experimental or prototype phases. There is a growing trend toward the development and deployment of low-cost, modular, flexible, and open-source systems for marine monitoring networks, fostering accessibility and scalability *(Butler et al. 2021)*.

The increasing interest in such solutions is driven by the high cost of commercial sensors and probes, which restrict the expansion of large-scale monitoring observatories, and prevent the maintenance of equipment and the continuity of historical time series. To address this, the scientific community has been actively developing cost-effective and open-source sensors to enhance either data availability or technological accessibility.

The PlanktoScope is an open-source hardware and software platform designed for precise, quantitative, and qualitative imaging of plankton communities. ©FairScope, McKenzie Powers

For example, microcontroller-based platforms such as Arduino and Raspberry Pi have facilitated the integration of low-cost sensors for oceanographic applications. These platforms enable real-time data collection and transmission, supporting a variety of sensor interfaces for monitoring parameters such as temperature, salinity, pH, dissolved oxygen, and turbidity. Additionally, low-power wireless communication technologies like LoRaWAN and NB-IoT are enhancing data transmission capabilities for remote marine observation.

Recent advancements include the development or adaptation of autonomous vessels, little buoys, aerial drones and miniaturized underwater robots, which provide cost-efficient alternatives to traditional oceanographic moorings, gliders, AUVs and ship-based measurements.

Open-source initiatives such as Smartfin, which equips surfboards with oceanographic sensors, and OpenCTD, a low-cost alternative to commercial conductivity-temperature-depth *(CTD)* sensors, have further expanded data collection possibilities *(Thaler et al. 2024)*.

These advancements, combined with cloud-based data platforms and artificial intelligence for automated data analysis, are transforming marine observation by making it more affordable, scalable, accessible, and efficient. This approach can be applied to a broad spectrum of applications, including climate change studies, coastal management, marine biodiversity monitoring, and pollution assessment.

Recent advancements in oceanographic instruments and marine observation systems have been driven by the need for cost-effective, scalable, and efficient solutions. Traditional oceanographic sensors and platforms, while highly accurate, have often been expensive and resource-intensive. However, new developments in technology have made ocean observation more accessible and cost-efficient.

A list of low-cost or cost-effective sensors and technologies can be found on the site scoop-ocean.org *(Solutions for Cost-effective Ocean Observation Platform)*, where a catalog of sensors and platforms including cost-effective technologies for ocean study is available.

Temperature

Temperature is a fundamental parameter in oceanographic observations, impacting salinity, density, pH, dissolved oxygen, and biogeochemical processes *(NOAA Ocean Service)*. Recent advancements in low-cost sensing technologies have expanded the range of reliable temperature measurement solutions, making high-accuracy observations more accessible.

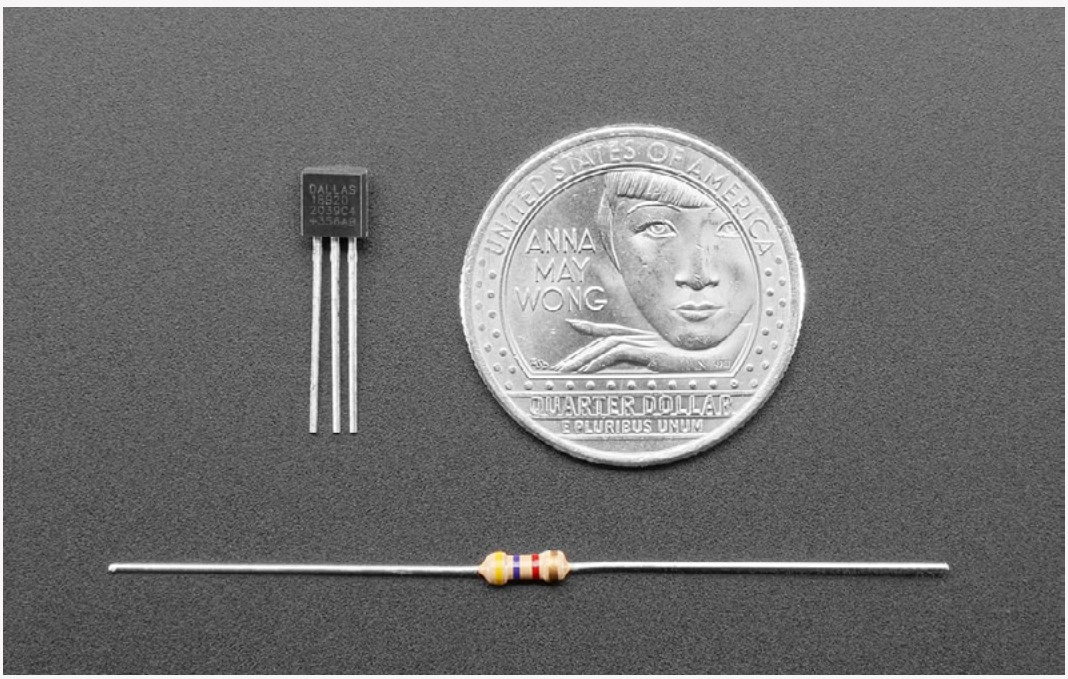
The selection of a sensing element is crucial for achieving modularity, stability, and accuracy. Platinum Resistance Temperature Detectors *(RTDs)*, such as PT100 and PT1000, remain widely used due to their excellent linearity and long-term stability. They offer varying levels of resolution and accuracy, aligning with the modularity concept. With improvements in sensor conditioning and calibration techniques, commercial circuits of high quality can now be obtained at significantly lower costs, sometimes for just a few dollars.

Thermistors remain a viable low-cost option, particularly for rapid temperature acquisition. However, their non-linearity necessitates advanced electronic compensation. Recent developments in signal processing and microcontroller-based correction algorithms have improved thermistor performance, enabling them to achieve accuracy and stability comparable to RTDs. NTC-type thermistors, when integrated into modern bridge circuits with advanced analog-to-digital converters, can now deliver highly precise measurements, reducing the cost barrier while maintaining performance.

Several manufacturers now provide reliable, affordable temperature sensors with improved accuracy and stability. Open-source electronics and IoT advancements have enhanced sensor integration, making real-time data transmission and remote monitoring more efficient. For instance, ATLAS Scientific offers a PT100 sensor with an accuracy of ±0.15°C, while Adafruit provides the DS18B20 digital sensor with an accuracy of ±0.5°C, both pre-wired and waterproofed. Unfortunately, the companies that sell those sensors do not provide information related to stability, which is a fundamental parameter in long-term observations. We therefore recommend a study testing the long-term stability.

Additionally, low-cost signal conditioning modules, such as PT100 analog-to-digital converters and amplifiers, are now available for as little as $15, supporting plug-and-play integration with new microcontroller generations.

Newer low-cost oceanographic instruments should incorporate AI-based calibration models and machine learning algorithms for drift compensation, significantly enhancing the stability of long-term observations. While commercial sensor solutions still often lack detailed stability information, ongoing improvements in cost-effective sensor calibration methods are bridging this gap, making these technologies more suitable for long-term deployments in marine research.



Digital temperature sensor from Adafruit. ©Adafruit

Sensors to Measure Salinity

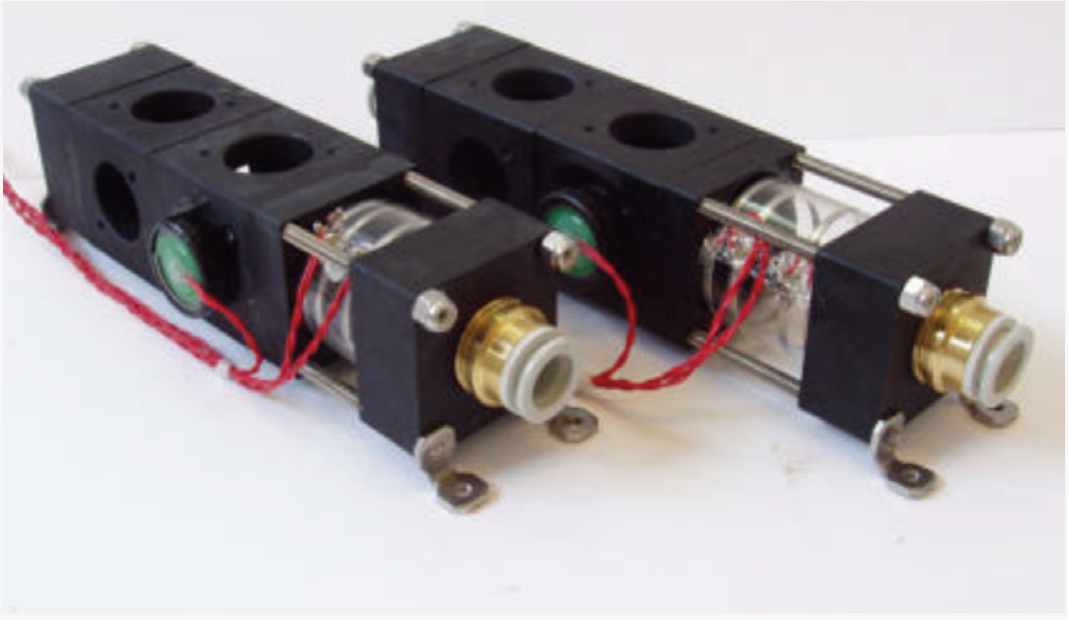
Salinity is the second fundamental variable for oceanographic and environmental applications, playing a crucial role in understanding ocean circulation, climate dynamics, and biogeochemical processes. In estuarine and coastal regions influenced by river discharge, salinity often correlates inversely with other biogeochemical variables that are more challenging to measure directly using automated instruments, such as nutrient concentrations and contaminants. A measurement accuracy of at least ±0.1 PSU is generally considered sufficient for many oceanographic and environmental monitoring applications.

Currently, traditional salinity measurement methods based on conductivity sensors and inductive cells remain the most reliable due to their established accuracy and robustness. They require an accurate, precise and stable temperature measurement to calculate salinity. However, they require high-quality circuits and effective anti-fouling strategies to ensure long-term deployment stability mainly for conductivity cells.

A high-resolution conductivity sensor has been developed for continuous flow measurement by mini-ferrybox, called SPECTRA, which has been tested both on Italian Coast Guard vessels, small coastal monitoring vessels and during the IOSMOS project *(Marcelli et al. 2014, 2016)*, with a resolution of 0.01 PSU.

While alternative methods, such as optical approaches, have been explored, they have not yet achieved the necessary sensitivity and reliability for widespread adoption in marine observation networks.

Among these, the use of inductive conductivity cells continues to be favored due to their simplicity, robustness, and reduced susceptibility to biofouling, as the sensing elements do not come into direct contact with seawater *(Parra et al. 2023)*. However, calibration remains a critical factor for maintaining measurement accuracy.



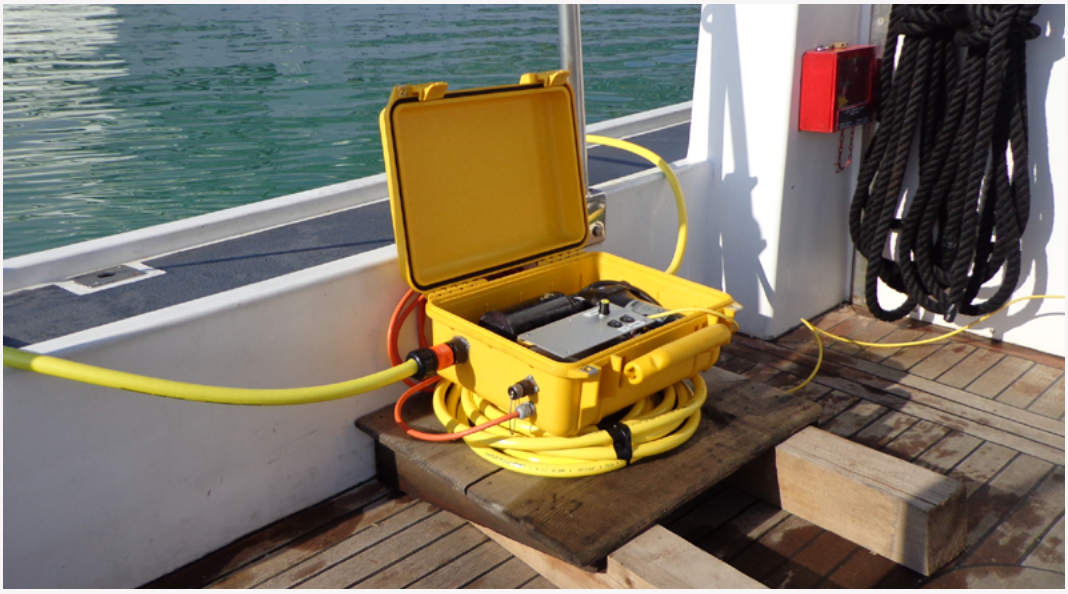
Modular components of the salinity measurement cells. ©Spectra technology

Recent innovations have introduced several alternative methods to traditional conductivity-based sensors. Some researchers have investigated optical techniques for estimating salinity, while others have experimented with integrating standard conductivity cell sensors into low-cost electronic platforms.

Examples of these approaches include:

- **Development of highly affordable conductivity cells** that leverage microcontroller-based signal processing has expanded access to salinity measurements in Citizen Science and educational applications *(Blanco-Gomez et al. 2023)*.
- Some studies have explored **the feasibility of using repurposed USB cables as low-cost salinity sensors**, demonstrating imaginative approach to development for DIY oceanographic monitoring *(Carminati et al. 2016)*.
- **Smartphone-Enabled Devices** that utilize smartphone cameras and sensors to measure refractive index and absorption properties of seawater have been proposed, providing a portable and accessible alternative for preliminary salinity assessments *(Hussain et al. 2017)*.

While these alternative technologies hold promise, their accuracy and stability remain insufficient for deployment in long-term marine observation systems. However, ongoing advancements in sensor miniaturization, AI-driven calibration algorithms, and IoT-enabled data acquisition systems may enhance their reliability in the near future.



FerryBox Installation for continuous measurement of Salinity, Temperature, Chlorophyll-a and CDOM. ©Spectra Technolgy

Turbidity, Chlorophyll A Fluorescence Sensors (Optical Sensors)

In recent years, various low-cost instruments for measuring both turbidity and chlorophyll a fluorescence have been developed and tested, although widespread field deployment remains limited. Due to challenges related to resolution and sensitivity at low concentrations, many existing sensors are not yet suitable for high-precision scientific applications. For reliable chlorophyll a fluorescence measurements, a resolution of at least 0.05 µg/L is required, while turbidity measurements in coastal waters demand a resolution of 0.1 NTU. To ensure data accuracy, these sensors must be calibrated against in situ water samples in addition to laboratory validation.

This section focuses on optical sensors for studying light, turbidity, and photosynthetic pigments *(primarily chlorophyll a)*. While certain chemical variables can also be measured with optical sensors, these will be discussed separately alongside traditional chemical sensing methods. In the following list a variety of low-cost optical sensors have been developed for aquatic monitoring.

One of the first low-cost chlorophyll a fluorescence devices was developed during the EU MFSTEP project: The T-FLAP *(Temperature and Fluorescence Launchable Probe)* was an expendable probe *(Marcelli et al. 2007)* that was tested by comparing the results with an SBE rosette equipped with a SCUFA fluorometer on CTD casts during several oceanographic cruises in the Mediterranean Sea, which led to the development of a modular, multi-purpose technology and therefore to a series of other applications *(CTD, etc.) (Marcelli et al. 2014)*.

Modular, low-cost profilers based on T-FLAP technology: from CTDs equipped with bio-optical fluorescence sensors *(chlorophyll a and CDOM)*, to specialized carbon-fiber profilers for polar seas and multispectral sensors.

Modular, low-cost profilers based on T-FLAP technology CTDs equipped with bio-optical fluorescence sensors (chlorophyll a and CDOM), ©T-FLAP technology

Murphy's Low-Cost Optical Sensor *(2015)*: Murphy developed a LED-based turbidity sensor comprising an LED array as a light source, two photodiodes, and a modular electronic system controlled by a custom data logger. The system demonstrated potential for continuous monitoring of turbidity in aquatic environments, though further refinement is needed for high-precision applications.

Turbidity sensors are widely used for environmental monitoring *(Matos et al., 2019)* and in fisheries and aquaculture, as monitoring increased turbidity in coastal marine environments is fundamental both for seawater quality assessment and because turbidity associated with aquaculture activities can negatively affect fish production.

To address this, researchers have developed low-cost turbidity sensors using LEDs and photoresistors to monitor water quality. These low-cost devices can be adapted for broader environmental monitoring applications, particularly in areas with variable freshwater and sediment inputs.

Following the improvement of the T-FLap *(Marcelli et al. 2016)*, ArLoc *(Arctic Low-Cost Probe)* was designed for Arctic environments *(Piermattei et al. 2018)*, as a modular, cost-effective probe capable of measuring pressure, temperature, and chlorophyll a fluorescence along the water column. Its adaptability allows integration with various observational platforms, making it a valuable tool for remote marine research in extreme conditions .

Advancements in miniaturised spectrophotometry, AI-assisted calibration, and IoT-enabled real-time data transmission are rapidly improving the performance of low-cost optical sensors. The integration of machine learning algorithms for automated calibration and drift correction holds significant potential for enhancing data reliability. Additionally, emerging biofouling-resistant coatings and self-cleaning mechanisms are being explored to extend sensor longevity in long-term ocean monitoring applications.

Specialized carbon-fiber profilers for polar seas and multispectral sensors. ©T-FLAP technology

Dissolved Oxygen Sensors

Dissolved oxygen *(DO)* is a critical parameter in marine environments, affecting aquatic life, water quality, and biogeochemical processes. Sensors used to measure DO typically employ electrochemical *(galvanic or polarographic)* or optical *(luminescence-based)* techniques to measure DO concentrations *(Bittig et al., 2018)*. Electrochemical sensors are often more affordable but may require frequent calibration and are susceptible to biofouling. In contrast, optical sensors offer advantages such as reduced maintenance and longer deployment durations due to their stability and resistance to biofouling *(Tengberg et al., 2006)*. A recent innovation in optical sensors for dissolved oxygen measurements is the introduction of fiber-optic-based sensors. The excitation and emission light are transmitted via an optical fiber between the sensor indicator and the oxygen meter, allowing for remote, miniaturised, and highly sensitive oxygen detection *(Borisov & Klimant, 2012)*. The development of low-cost DO sensors has expanded the capacity for extensive and continuous monitoring in oceanographic research, aquaculture and environmental management. Manufacturers such as DFRobot[7] and Atlas Scientific[8] have introduced a range of affordable DO sensors with different specifications to meet different monitoring needs.

Oxygen Sensor (calibrated) ©DFRobot

7 www.dfrobot.com
8 www.atlas-scientific.com

Recent developments have focused on improving the affordability and functionality of these sensors. For example, a study has introduced a microbial fuel cell-based DO sensor that operates with minimal maintenance over long periods of time, demonstrating comparable performance to commercial sensors at a fraction of the cost *(Sun et al., 2022)*. In addition, the integration of DO sensors into low-cost sensor buoy systems has facilitated real-time monitoring of shallow marine environments, providing valuable data for environmental assessment. Challenges remain in ensuring the long-term accuracy and reliability of low-cost DO sensors in dynamic marine conditions. Issues such as sensor drift, biofouling and calibration stability require ongoing research and development. A systematic review highlighted the need for rigorous validation of low-cost water quality sensors, emphasizing that many studies lack comparisons with reference devices, which is crucial for establishing measurement reliability *(De Camargo et al., 2023)*.

Validation in the field, integration in fisheries observing systems and functionality demonstrations of cost-effective optical DO *(and Chl-a sensors)* have also been carried out within the NAUTILOS H2020 project *(Martinelli 2023a)*.

Nutrients

The accurate measurement of seawater nutrients remains a significant scientific and technological challenge due to the wide spatial and temporal variability of marine environments, which leads to substantial differences in nutrient concentrations. This complexity continues to hinder the standardisation and harmonization of in situ nutrient measurements *(Daniel et al., 2019)*. While laboratory-based analytical techniques provide high-precision measurements for most major nutrients, such as nitrate, phosphate, and silicate, in situ sensing technologies still face several limitations. These include issues related to calibration accuracy, sensitivity to low concentrations, environmental interferences, and variability in deployment conditions *(Mowlem et al., 2021)*.

A diverse array of commercial in situ nutrient sensors is now available, as documented in the Alliance for Coastal Technologies *(ACT)* database. However, many of these instruments suffer from high power consumption, elevated costs, limited sensitivity to trace concentrations, and reduced autonomy for extended or remote deployments *(Moore et al., 2009)*. Although affordable, low-cost nutrient sensors are not yet commercially widespread, recent advancements in miniaturised optical and electrochemical technologies are showing promise. Several prototypes are currently under development, aiming to improve accessibility for long-term ocean monitoring programmes *(Zhu et al., 2024)*.

pH and pCO_2

As with oxygen sensing, chemical sensing in marine environments remains crucial for monitoring ocean health and biogeochemical processes. Some parameters, particularly pH, can be measured using relatively low-cost sensor technologies. For instance, electrochemical pH sensors such as the DFRobot Gravity: Analog pH Sensor Meter Pro Kit *(H-101)* are compatible with Arduino platforms and retail for approximately €45 or less, offering an accuracy of ±0.1 pH units. Atlas Scientific also offers a variety of pH probes and monitoring tools at a range of price points, depending on durability and stability requirements *(Méndez-Barroso et al., 2020)*.

Innovative, miniaturised technologies are emerging. Pinto et al. *(2019)* introduced a low-cost *(~€100)*, lab-on-a-chip pH sensor for seawater based on spectrophotometric analysis. This system is notable for its compact design, low power consumption, and potential for integration into autonomous platforms. Despite these advancements, most low-cost pH sensors remain insufficiently robust for long-term deployment in marine environments due to challenges related to calibration, biofouling, and sensor drift over time.

Alternative pH sensing approaches include optical sensors based on fluorescence changes in dye-coated fibre optics and sensors employing ISFET *(Ion-Sensitive Field-Effect Transistor)* technologies, which offer enhanced pressure compensation and stability *(Martín et al., 2006; Johnson et al., 2016)*. However, these systems still incur relatively high production and maintenance costs, which limit their widespread adoption for routine ocean monitoring. With careful maintenance and calibration procedures, ISFET pH sensors can be used for monitoring ocean pH at ~<0.01 uncertainty *(Kapsenberg et al., 2017)*.

As for partial pressure of CO_2 *(pCO_2)*, the technology has reached a moderate level of maturity. Commercial sensors are available for deployment in coastal and open-ocean settings, though they often face constraints in terms of depth range, calibration, equilibration time, and data acquisition frequency. Many systems rely on gas-permeable membranes that equilibrate with seawater CO_2, followed by detection using infrared *(IR)* absorption or colorimetric spectrophotometry *(Wang et al., 2019; Liu et al., 2023)*. While the cost of electronic and optical components is gradually decreasing, these sensors are not yet widely considered cost-effective for long-term autonomous use in large-scale observation networks.

Passive Acoustic (Hydrophones)

Marine bioacoustics uses sound to study marine life and ecosystems, as sound travels efficiently underwater. Hydrophones support research on species, ecosystem health, and conservation. Yet, high costs and technical demands limit their accessibility in education, Citizen Science, and low-income regions.

To address access gaps, ***"Ocean Sound"*** is now an Essential Ocean Variable *(EOV)* per GOOS. The International Quiet Ocean Experiment *(IQOE)*, co-sponsored by the Scientific Committee on Oceanic Research *(SCOR)* and the Partnership for Observation of the Global Ocean *(POGO)*, promotes the development of affordable, high-quality autonomous hydrophones.

While most existing autonomous hydrophone units cost in excess of $3,000 USD, less expensive alternatives often lack the requisite recording fidelity and power management features, limiting their practical application in long-term passive acoustic monitoring *(PAM)*.

Through the support of POGO, 25 prototypes of low-cost hydrophones will be developed and distributed globally for testing by a diverse range of end-users. This initiative focuses on the design of an affordable, open-source autonomous hydrophone system that maintains high standards of quality and performance while serving the needs of research, education, and community science. In parallel with the device, dedicated software and a global digital educational platform will be developed to promote and facilitate its adoption and use.

To address these limitations, in 2023, IQOE and POGO launched a Task Team to develop low-cost hydrophones for research and education. This interdisciplinary group promotes an open-source, modular, autonomous system under $200, aiming to expand global access to underwater acoustic monitoring for science, conservation, and citizen engagement.

Technological advancements have improved sustained acoustic monitoring, with affordable hydrophones enabling real-time, large-scale, and cost-effective marine soundscape surveillance *(Sousa-Lima et al., 2013)*. These tools facilitate early detection of noise pollution and strengthen conservation efforts. Additionally, machine learning for automated sound classification and Citizen Science platforms expand bioacoustic monitoring, enhancing its reach and impact *(Nieto-Mora, 2023)*.

The democratisation of marine acoustic science fosters scientific progress while promoting public engagement, educational outreach, and participatory conservation, especially in underserved regions lacking research infrastructure *(Wall et al. 2025)*.

Through the support of POGO, 25 prototypes of low-cost hydrophones will be developed and distributed globally for testing by a diverse range of end-users. This initiative focuses on the design of an affordable, open-source autonomous hydrophone system that maintains high standards of quality and performance while serving the needs of research, education, and community science. In parallel with the device, dedicated software and a global digital educational platform will be developed to promote and facilitate its adoption and use. ©Lucille Chapuis

Plankton

The PlanktoScope by FairScope is an innovative, low-cost imaging device designed for high-throughput quantitative imaging of plankton samples in aquatic biology and ecology. The PlanktoScope is a modular, open-source hardware and software platform that allows for high-throughput quantitative imaging of plankton samples in aquatic biology and ecology. Its small size, ease of use, and low cost make it suitable for deployment in a range of applications, including the monitoring of laboratory cultures or natural microplankton communities. The PlanktoScope can be controlled from any Wi-Fi-enabled device, and its versatility allows for rapid reconfiguration to match the evolving needs of the user, including citizen scientists.

The PlanktoScope is an open-source hardware and software platform designed for precise, quantitative, and qualitative imaging of plankton communities. ©FairScope, photography by Maud De Hemptinne

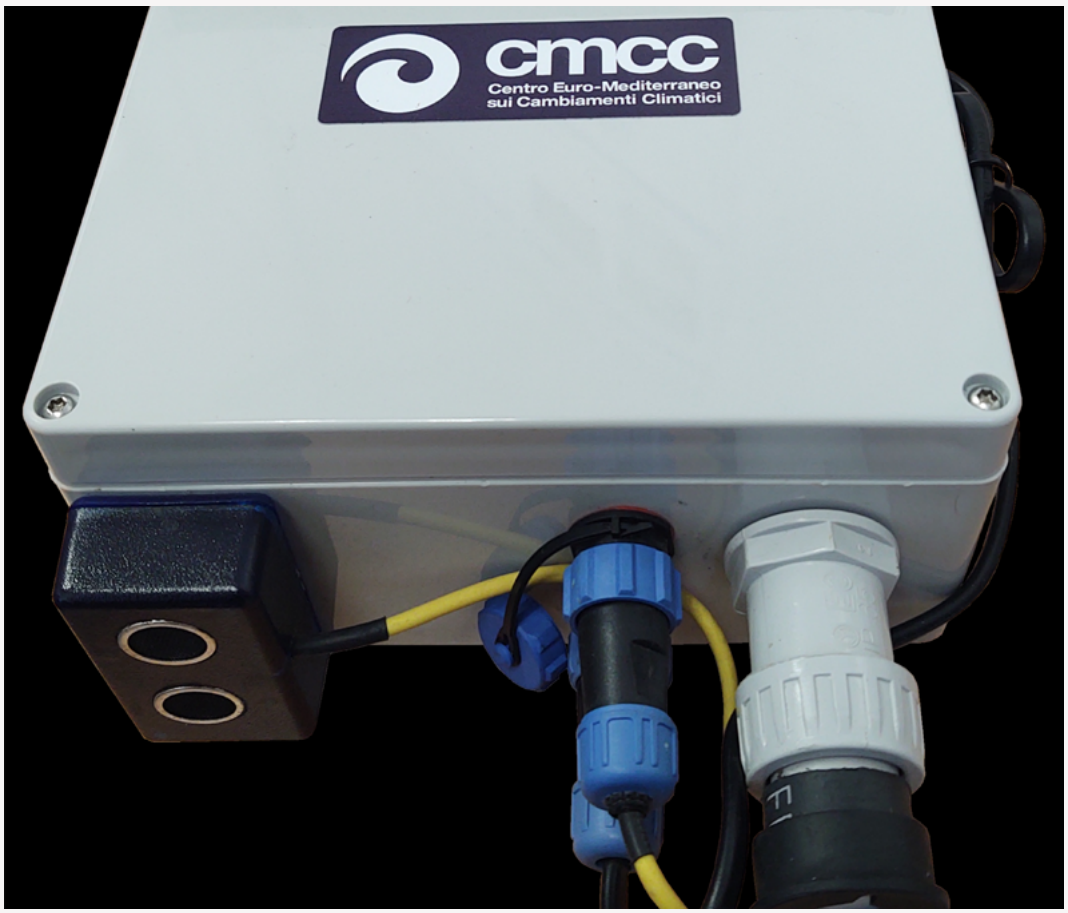
Sea Level, Waves, and Currents

Sea Level

Tide gauges: The GLOSS community has actively sought low-maintenance, cost-effective solutions to support a growing variety of tide gauge applications. Traditional float and subsurface pressure sensors *(placed below the lowest low tide)* have largely been replaced by non-contact systems, such as acoustic and radar gauges. These obtain sea level by measuring the time it takes for ultrasonic *(acoustic)* or microwave *(radar)* pulses to travel from a transmitter to a receiver, reflecting off the water surface. Radar sensors, now widely used in many national networks, offer reliable performance without stilling wells and are less affected by environmental factors *(IOC-UNESCO, 2016)*. Inter-comparison studies confirm that most technologies meet the GLOSS accuracy standard *(<1 cm)*; installation conditions such as wave exposure and other factors often influence performance more than the sensor itself *(Woodworth and Smith, 2003; Martín Míguez et al, 2005, 2008; Pérez-Gómez et al., 2014)*. The station's intended use ultimately guides the choice of new technology and installation approach.

CMCC Interbox, a low-cost development to measure sea level, surface water temperature, atmospheric pressure, relative humidity and air temperature. ©Centro euro-Mediterraneo sui Cambiamenti Climatici (CMCC)

For example, very low-cost acoustic sensors with real–time data transmission have been deployed in recent years to densify tsunami warning networks in many regions, or to measure tidal changes in coastal environments at a fraction of the cost of traditional float tide gauges *(Frank-Comas et al., 2021; Zacharia et al., 2011; Pérez-Gómez et al., 2022)*. Radar or acoustic sensors, with steadily decreasing prices for some manufacturers, provide multiple benefits, including precise measurements *(especially radar sensors)*, non-intrusive operation, quick deployment, cost-effectiveness, and the capability for real-time data collection. They are also highly adaptable, allowing integration with a wide range of data logging systems. Their minimal maintenance requirements and ability to withstand harsh marine conditions further enhance their appeal. Some of these sensors, usually more expensive, measure the whole spectrum of water level oscillations, providing not only sea level but also waves and infragravity waves parameters inside the ports *(García-Valdecasas et al., 2020)*. In a harbour environment, these sensors are especially valuable for monitoring waves and water levels in areas with high traffic and varying tidal conditions, which is essential for effective harbor management, safe vessel navigation, and ensuring efficient docking operations *(Pérez-Gómez et al., 2022)*. Some examples of manufacturers offering these types of sensors include: MIROS *(SM-140 RangeFinder)* or Coastal-e-Solutions *(WaveGaugeUltra)*.



CMCC Interbox sensors ©Juan Martinez

In addition, tracking other variables at tide gauges such as atmospheric pressure, wind, air temperature, precipitation, or humidity is crucial for gaining deeper insights into the mechanisms behind water level fluctuations, storm surge behavior, and compound flooding events. CMCC *(Centro euro-Mediterraneo sui Cambiamenti Climatici)* has developed a very low-cost ultrasonic sensor integrated with sensors *(InterBOX)* for measuring air humidity, temperature, atmospheric pressure, and precipitation. It has been installed at various sites around the world and automatically sends data to EMODnet *(Juan Martinez et al., 2025)*.

For precise assessments of sea level rise *(typically on the order of a few mm per year)*, long-term stability of the sensor reference or datum, as well as the ability to measure simultaneous ground motions, is essential. For the latter, GLOSS recommends co-location of tide gauges with Global Navigation Satellite System *(GNSS)* receivers *(IOC/UNESCO, 2012)*, with an increasing number of GNSS co-located tide gauges worldwide. The GNSS receivers can also provide water level data using interferometric reflectometry *(GNSS-IR)*, a novel technique which could largely expand the coastal sea level network through exploitation of existing permanent GNSS receivers installed near the sea *(Larson et al., 2017; Williams et al., 2020)*. Ongoing studies try to identify the processes that can be measured, and the limitations of this technology, as well as the potential use of very low-cost GNSS sensors including those in smartphones, despite their lower accuracy, for tidal measurements in regions where maintenance of conventional tide gauges is challenging *(Li Y et al., 2021, Oreiro et al., 2024)*.

As part of the European Union EuroSea project, a new low-cost and largely maintenance-free tide gauge system was developed by the UK National Oceanography Centre *(NOC)* in collaboration with Puertos del Estado *(Spain)*, to meet GLOSS requirements for aforementioned applications. Powered by renewable energy, the system supports high-frequency sampling for tsunami monitoring, with two radar sensors providing redundant sea level measurements, and employs dual, low-cost telemetry methods for data transmission. A station was installed in Barcelona in 2023, and data are sent to the GLOSS real-time data portal: Sea Level Station Monitoring Facility. It also integrates GNSS Interferometric Reflectometry *(GNSS-IR)* to measure both sea level and vertical land motion, eliminating the need for conventional levelling. In Spain, the Spanish Hydrographic Institute has recently installed several tide gauge stations, based on low-cost acoustic sensors, co-located with low-cost GNSS, which provide sea level, waves and infragravity waves parameters, and include sensors of atmospheric pressure, air temperature and humidity. These new platforms *(DEEP WAVES-RTK)* have been developed by Deep Insight *(Mareógrafo Avanzado. Nivel del mar, agitación, onda larga)* and transmit data to the Copernicus Marine Service In Situ TAC.

The examples presented are only a subset of all ongoing initiatives in many countries. A working group for addressing the challenge to test new low-cost options and novel techniques such as the GNSS-IR was established by the last GLOSS Group of Experts meeting in Panamá, in March 2025.

Waves

In recent years, there has been growing[9] interest in the creation of compact, affordable, and lightweight buoys designed to measure waves at the ocean surface *(Collins et al. 2024)* including solutions from ships *(Rossi et al. 2021)*.

In recent years, several technological developments have been carried out for measuring wave motion. In some cases, for shallow waters, arrays of pressure transducers have been used, which in those conditions provide a reliable and low-cost solution. A buoy based on Arduino has also been developed for surface wave measurements *(Yurovsky et al., 2017)*. In other cases, LoRaWAN technology has been employed for real-time data transmission to shore, reducing costs in the data transmission system *(Majumder et al., 2024)*.

A more advanced technological solution has been developed with the Scripps Wave Drifter, which, when used as a fixed wave buoy, provides significant improvements though it is not low-cost but rather cost-effective. The Scripps Wave Drifter *(Directional Wave Spectra Drifter – DWSD)* can now be anchored to operate similarly to a traditional buoy, while capturing high-frequency wave data. Its GPS-based wave measurement offers notable advantages, including the absence of mechanical moving parts that would otherwise require delicate handling and maintenance.

Currents

The study of marine currents is vital for understanding ocean dynamics, coastal processes, ecosystem health, and the implications of climate variability. Traditionally, current measurement relied on expensive and complex instruments such as Acoustic Doppler Current Profilers *(ADCPs)*, limiting spatial and temporal resolution due to cost and deployment constraints. In recent years, however, the development of low-cost, high-performance sensors has enabled broader access to oceanographic monitoring. Among the most promising tools in this category are drag-tilt current meters, such as the TCM-1 Tilt Current Meter *(Gonzàlez et al., 2025)* by Lowell Instruments[10] and the Marotte HS developed by the Marine Geophysics Laboratory at James Cook University[11] . The TCM-1 and Marotte HS are low-cost drag-tilt current meters that use accelerometers and magnetometers to estimate current speed and direction based on device tilt. Both are compact, battery-powered, and store data on microSD cards, making them ideal for long-term, autonomous deployments. Their affordability and simplicity support widespread use in nearshore environments like reefs, estuaries, and aquaculture sites. Another example is the one of ***"smart"*** drifters, called ***"Marine Litter Trackers"*** *(MLT)*, developed and used by CNR-ISMAR in the framework of NAUTILOS project.

9 map.emodnet-physics.eu/platformpage/?platformcode=TG_RIM_01&source=cp&integrator=CMCC
10 lowellinstruments.com/products/tcm-1-tilt-current-meter
11 www.marinegeophysics.com.au/current-meter

They have been used to track the movements of real anthropogenic marine debris *(AMD)* from rivers to the sea, using modern software and hardware consumer technologies and the GSM and LoRa networks instead of satellite communication, a solution presenting important advantages in terms of costs and energy consumption *(Merlino et al. 2023a)* for near-shore applications. This innovative type of drifter proved to be very cheap but also reliable, robust and self-powered *(solar cell)*, presenting almost no maintenance costs. They can be built not only by those trained in the field but also by those with no specific expertise, including technical high school students and association, simply by following the instructions. The potential of this open-source approaches enables their use in Citizen Science contexts.

In this context, the open-source development of a low-cost CODE-type drifter by the OGS *(Istituto Nazionale di Oceanografia e di Geofisica Sperimentale)* is particularly relevant. The OGS has published a technical report *(Gerin et al., 2016)* that provides detailed instructions for the self-construction of a drifter using low-cost components.

Low-cost drifter ©OGS

Animal Borne Sensors

Animal-borne ocean sensors are miniaturized devices temporarily attached to marine animals *(such as seals, whales or turtles)* in order to collect environmental data about remote and inaccessible ocean habitats data while they go about its natural movement and behavior. These compact sensors, which are typically glued to animals using non-harmful adhesives or temporary harnesses, can measure essential ocean variables like temperature, salinity, depth *(pressure)* or ocean currents, among others. They are designed to fall off naturally after a period or be removed when the animal is recaptured.

This approach benefits from the fact that marine animals use to follow biologically important routes *(like migration paths or feeding zones)*, providing a useful insight into marine regions that are often difficult or expensive to reach with traditional ocean monitoring platforms such as moored buoys or ships. Air-borne ocean sensors can significantly contribute to improve ocean circulation forecast models or to track climate change effects in polar regions.

Within this context, It is worth mentioning AniBOS *(Animal Borne Ocean Sensors)* as an emerging component of GOOS that has been endorsed as a UN Ocean Decade Action *(McMahon et al., 2021)*. It provides freely available oceanographic data collected through bio-logging, deploying sensors on marine animals, filling an important observational gap through the integration of animal-collected data within the GOOS *(McMahon and Fabien, 2022; March et al., 2020)*.

Marine organisms can contribute *(AniBOS)* to the acquisition of oceanographic data. Recent technologies and advances in miniaturization have minimized disturbance to the organisms.

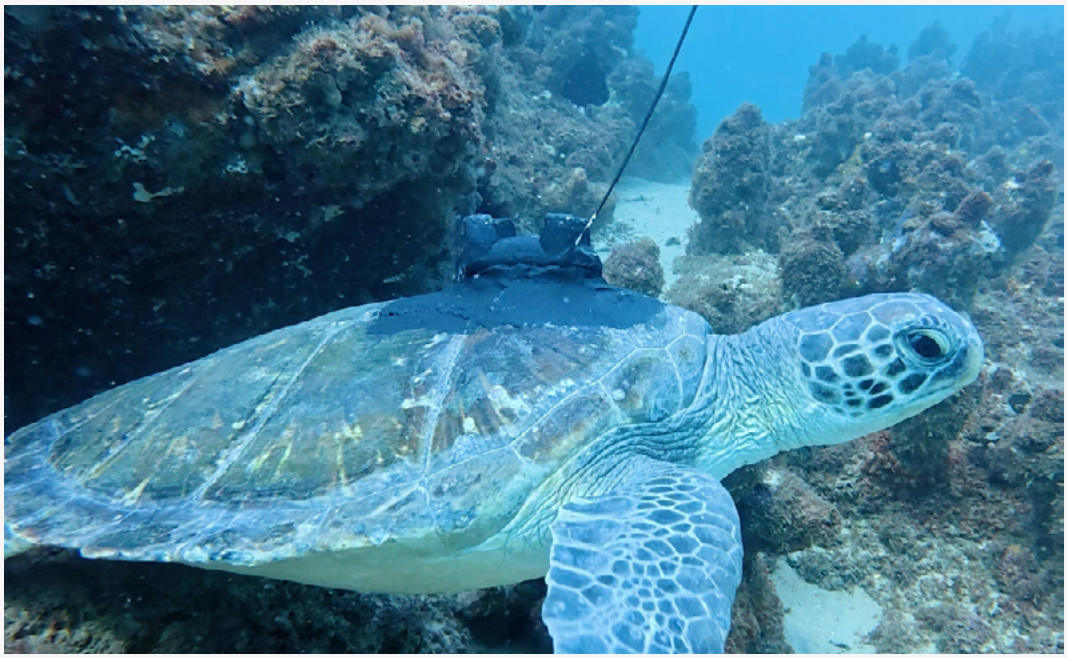
A complementary example at local scale is the Oasis Programme[12], aimed to unveil a new perspective on the role of sea turtles in marine ecosystems. Coordinated by SOCIB, this project stood out for its innovative operational ecology and dynamic ocean management approach, using the loggerhead turtle *(Caretta caretta)* in the Western Mediterranean as a case study.

Marine organisms can contribute (AniBOS) to the acquisition of oceanographic data. Recent technologies and advances in miniaturization have minimized disturbance to the organisms. The Oasis program and the SNO MEMO program provide very low-cost data that are integrated into their respective observational systems. ©Isobel Lerpiniere, AniBos

12 www.socib.es/ca/actualitat/ocean-currents-and-turtles-the-oasis-program-for-marine-conservation

The SNO MEMO *(Service National d'Observation – Microorganismes et Écologie Marine Organisée)*[13] offers a pioneering low-cost approach to ocean observation by integrating biological platforms, specifically, marine animals, into its monitoring strategy.

Central to this approach is the use of animal-borne sensors, small and lightweight instruments attached to free-ranging species such as seals, turtles, or fish. These mobile platforms allow researchers to collect physical, chemical, and biological ocean data across vast and often inaccessible regions, without the need for expensive ship time or permanent infrastructure. The sensors typically record temperature, salinity, depth, and even microbial or eDNA samples, enabling MEMO to gather high-resolution data in real time or upon tag recovery. This method drastically reduces costs compared to traditional autonomous floats or fixed buoys while offering unparalleled spatial coverage. Moreover, animal-borne sensors enable continuous monitoring in dynamic or remote environments, such as polar regions or mesopelagic zones, which are often poorly sampled. The MEMO programme emphasises modularity and standardisation in its sensor packages, ensuring compatibility with European data infrastructures and enabling collaborative reuse of collected data. By leveraging the natural behavior of marine animals, MEMO turns existing ecological processes into observational assets, achieving both ecological insight and economic efficiency. This innovative approach exemplifies how technological miniaturization and ecological intelligence can be combined to revolutionize ocean monitoring in a sustainable and cost-effective way.



Animal-Borne Ocean Sensors (AniBOS), emerging network of the Global Ocean Observing System (GOOS): marine turtle Instrumented with an sensor. ©Robert Harcourt

13 www.sextant.ifremer.fr/geonetwork/srv/api/records/8c8c52b3-4b00-4d11-9dad-37edf6395d82

eDNA

Environmental DNA *(eDNA)* has the potential to transform biodiversity monitoring, but in addition to standardised protocols and validation procedures, high costs remain a major obstacle to a broader uptake, especially in resource-limited settings *(Yamahara et al., 2025)*. Recent innovations have focused on automating the water sampling, filtration, and preservation procedures, simultaneously reducing personnel and per sample costs and enhancing reproducibility across sampling events. Notable examples include the DOT eDNA sampler *(Hendricks et al., 2023)*, the Smith-Root eDNA AutoSampler *(George et al., 2024)*, the Automated Filtration System for Marine Microbes *(AUTOFIM; Metfies et al., 2020)*, the In Situ Autonomous Biosampler *(IS-ABS, Ribeiro et al., 2019)* and the Filtering Instrument for DNA Observations *(FIDO) (for full overview see Liu et al., 2024; Yamahara et al., 2025)*. Despite their efficiency and state-of-the-art design, these systems typically cost between €25,000 and €70,000, posing a significant financial barrier.

In contrast, low-cost alternatives such as the open-source SASe Sampler *(~280 USD, Formel et al., 2021)*, the Smith-Root eDNA Citizen Scientist model *(Ref 1, 2,153 USD)*, the TorpeDNA and the DNautic samplers *(Ref 1)* offer more accessible options, particularly for Citizen Science initiatives. However, these budget-friendly devices may or may not compromise on key aspects such as reproducibility, functionality, ease of use, robustness, operational versatility or the ability to collect multiple samples autonomously.

The Smith-Root Autosampler is a simple and affordable automated eDNA sampling system capable of collecting up to 8 eDNA samples on a user-defined schedule. ©Smith-Root

2.3. Low-Cost Technologies and Citizen Science

Citizen science has emerged as a valuable methodology for collecting environmental data in a cost-effective and logistically efficient manner, particularly in the field of biological oceanography. Numerous initiatives have harnessed volunteer efforts to gather data relevant to marine ecosystems, thus expanding observational capabilities beyond traditional scientific infrastructures *(Lauro et al., 2014)*. In this collaborative model, trained non-specialists contribute to scientific investigations by adhering to standardised data collection protocols, thereby enhancing spatial and temporal coverage of environmental datasets *(French et al. 2017)*.

The integration of Citizen Science in marine research is facilitated by two main factors. First, the proliferation of low-cost and user-friendly technological tools, in particular mobile phone apps, has democratised access to ocean data acquisition, enabling broader participation by non-professional contributors. Second, the data produced through such initiatives often supplement formal scientific observations, particularly in under-monitored or remote regions *(Falco et al., 2007)*. This approach is especially pertinent in developing countries, where engaging local fishing communities can provide dual benefits: enhancing community awareness and supplying researchers with valuable data for ecological and fisheries management.

The Mangōpare sensor is a robust and simple device that attaches to fishing gear and collects data.
©Moana Project partner ZebraTech

One notable pilot initiative in this domain is the Fishery Observing System, which demonstrated the feasibility of integrating artisanal fishers into a broader observational network *(Falco et al., 2007)*. A key recent example is the New Zealand's Moana project. Scientists partnered with the commercial fishing industry and deployed over 300 sensors measuring subsurface temperature subsequently integrated on the EMODnet platform *(Jakoboski et al., 2024)*. Sustainability remains a cornerstone for the success of these initiatives, with the affordability and durability of sensor technologies playing a decisive role.

A prominent example of innovation in Citizen Science tools is the Smartfin project, which integrates temperature sensors into surfboard fins to capture thermal data in surf zones—areas that are typically under-sampled by conventional oceanographic platforms *(Bresnahan et al., 2017)*. This model exemplifies how recreational water activities can serve as effective platforms for continuous data acquisition *(Brewin et al., 2017)*. Similarly, sailing boats have been equipped with sensors to gather oceanographic data across broad transects, demonstrating the viability of long-term, low-cost monitoring.

Technological miniaturization *(Piermattei et al. 2018)* has further expanded the applicability of Citizen Science, particularly in coastal zones where temperature profiling and water quality monitoring are essential. Projects led by institutions such as the Central Marine Fisheries Research Institute *(CMFRI, 2018)* have successfully deployed low-cost sensors for such purposes. FThe incorporation of smartphone-based tools has revolutionized environmental sensing. For instance, the SmartFluo prototype device, developed under the European FP7 project CITCLOPS, utilized smartphone components to measure chlorophyll a fluorescence, enabling users to assess phytoplankton concentrations at minimal cost *(Friedrichs et al., 2017)*.

Additionally, initiatives such as CoastSnap, have leveraged the potential of using smartphones to monitor coastline changes. They have developed a mobile application where citizens at specific CoastSnap stations worldwide can upload daily observations of their coastlines *(Harley and Kinsela, 2022)*.

Citizen Science approaches have been used also to realize and use special smart drifters *(Marine Litter Trackers – MLT)* to follow the dispersion of anthropogenic objects in the sea. The possibility of self-building such drifters and the low–cost of the technologies used *(Arduino, Maduino, Internet Of Things components)* make it possible to increase the number of dispersion experiments that can be carried out, and therefore the number of data collected.

Institutional frameworks have also recognized the strategic potential of Citizen Science. The Phytoplankton Monitoring Network *(PMN)*, initiated by the National Centers for Coastal Ocean Science *(NCCOS)* under NOAA, mobilizes volunteers to monitor the composition and distribution of harmful algal blooms *(HABs)*, enhancing both early warning capabilities and public engagement *(Morton et al., 2015)*.

Other notable Citizen Science efforts include the Jellywatch Programme for monitoring jellyfish outbreaks *(Boero et al., 2009)*, the Reef Check initiative for coral reef health assessments *(Hodgson, 2001)*, and the Sea Search Koss programme focused on coastal marine biodiversity *(Koss et al., 2009)*. A comprehensive overview of the advancement and strategic integration of Citizen Science into European marine research frameworks was provided by the European Marine Board *(García-Soto et al., 2017)*.

Despite their promise, Citizen Science initiatives require robust data validation frameworks to ensure scientific reliability. Future projects could explore the following areas such as Machine Learning for data validation and cross-sectoral integration*(e.g., Copernicus Marine Service)* to optimize data utility and capacity building in the Global South. Targeted training and technology transfer programmes for coastal communities in the tropics and subtropics could be developed, as well as open-source sensor platforms promoting DIY oceanography kits that would allow volunteers to build, calibrate, and deploy their own sensors.

Citizen Science is a valuable avenue for marine data collection, leveraging popular participation and crowdsourcing to transform daily operations into opportunities for measurement. Beyond the citizen level, this approach extends to platforms of opportunity and autonomous systems that gather information while the sea is being used for other purposes. Its main advantage lies in expanding data acquisition through low-cost technologies; however, it should remain distinct from dedicated monitoring systems. To ensure reliability, Citizen Science requires rigorous data quality control, dedicated databases capable of aligning its outputs with other datasets, and validation through specific intercalibration programmes, warranting separate and detailed treatment.

Oceanography for Everyone 2024 OpenCTD workshops. ©Allie Wilkinson

2.4. Cost-effective Approach

Observing Platforms

Understanding cost-effective ocean observing platforms requires a comparison with the high expenses of traditional research vessels, which include both capital and operational costs. Purchase prices range from over €15 million for smaller coastal ships *(e.g., Coriolis of The Helmholtz-Zentrum Hereon)* to €124 million for mid-sized global vessels *(Sonne II of the German Federal Ministry of Education and Research)* and up to €1.185 billion for new generation icebreaking ships like the new German polar research and icebreaking vessel currently under construction to replace the original Polarstern expected to be delivered and enter service around 2030.

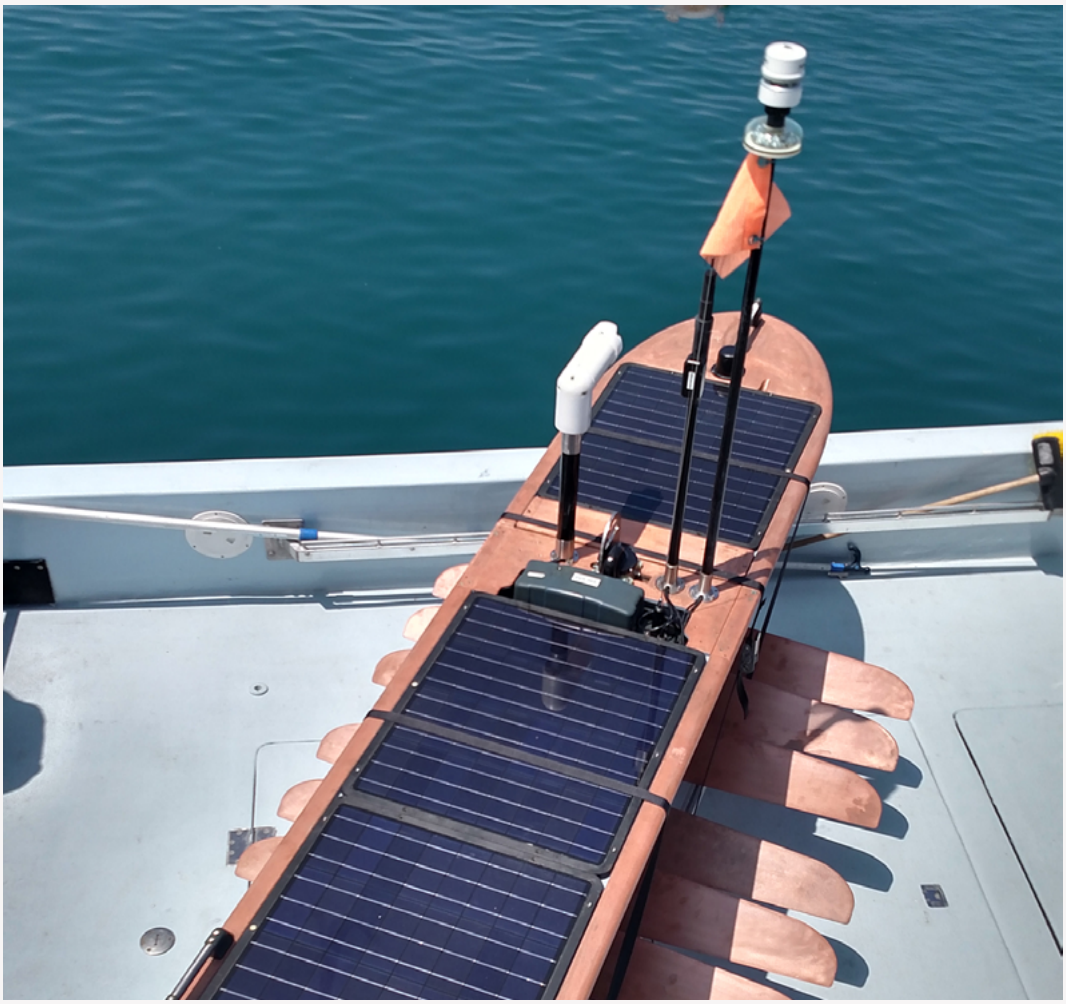
Operational costs can vary from $4,000–$16,000 USD per day *(UNOLS fleet; Li et al., 2023)* and can reach >€70,000 daily for large ice-breaking vessels. Notably, 55% to 80% of these expenses stem from crew wages and fuel *(Ref 1)*. Therefore, reducing staffing and fuel demands is key to lower costs for ocean observation platforms. This can be achieved by 1) autonomous fuel-free operation, 2) low-cost open-source technologies or 3) collaboration with non-scientific platform owners.

The rise of ocean observing technologies has led to a variety of unmanned, battery– or solar-powered platforms. A widely used example is the ARGO float, costing between $25,000 and $185,000, with over 4,100 units deployed globally *(Ref 1)*. While ARGO floats drift passively, self-navigating unmanned vehicles are categorized into Unmanned Aerial Vehicles *(UAVs)*, Unmanned Surface Vehicles *(USVs)*, and Autonomous Underwater Vehicles *(AUVs)*. These provide high-resolution imagery, atmospheric or oceanographic measurements in coastal and polar regions after being deployed from a ship. Drones can be easily equipped with light-weight sensors and may even cost less than 100 USD.

Examples of USVs are SailDrones costing 1.5-7.5 million per drone and 100 USD hourly operating costs or the Wave Glider[14] that can be powered by wind and solar energy, costing between $140,000 – $500.000 *(Ref 1)*. The AUVs can be further grouped in untethered robots that perform pre-programmed missions beneath the ocean surface or gliders that move through the water column by adjusting their buoyancy. Stationary autonomous platforms can include Benthic Landers that are deployed to the seabed or autosamplers operated in coastal waters from the surface *(e.g. WILMO, Deschner et al. 2024)*. Costs can vary from $50.000 *(Sparus II, Ref 1)* to $130,000 *(Javelin AUV, Ref 1)* or $175,000 for the Wave Glider SV2 *(Ref 1)*.

14 www.liquid-robotics.com

In contrast to proprietary ocean observing platforms, open-source platforms that can include open-source autopilot software represent a significant milestone in further reducing costs and democratising access to ocean observing platforms. These solutions span a wide range of applications, including USVs, Autonomous Surface Vehicles *(ASV) (e.g. ImpYak)*, underwater drones *(ArduSub, LoCO AUV)*, sensor platforms *(OpenCTD, SmartFin)*, the underwater gliders *(OSUG)*, benthic landers *(KOSMOS 3.0)*, moorings *(AusOcean Rig)*, and drift buoys[15] *(Butler & Pagniello 2022 Merlino et al. 2023a)*. Many of these platforms are available for under $5,000, and some for less than $1,000, making them accessible to a broader community of researchers, educators, and citizen scientists.



Wave energy is greatest at the water's surface, decreasing rapidly with increasing depth. The Wave Glider's unique two-part architecture exploits this difference in energy to provide forward propulsion. ©Liquid Robotics

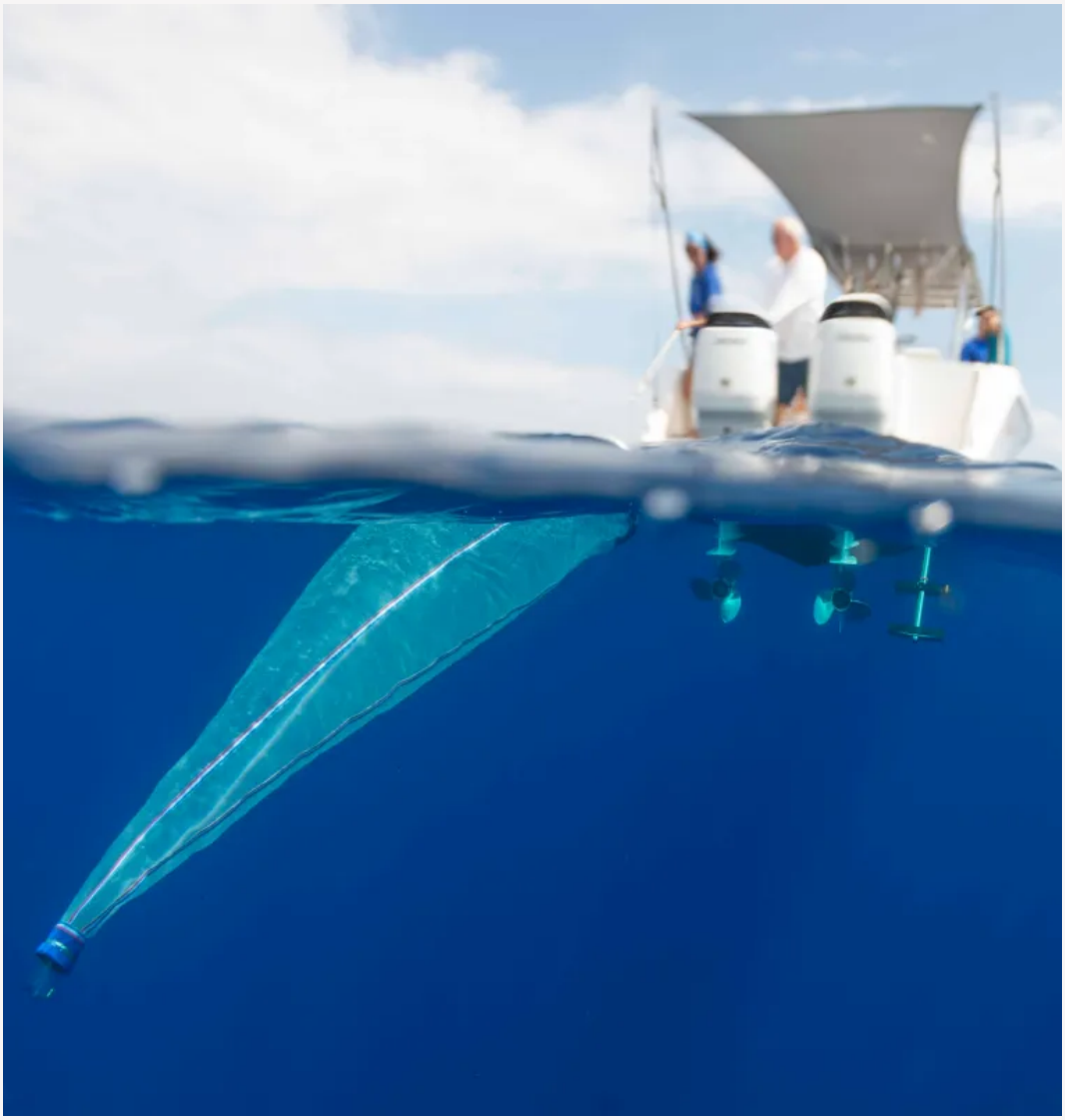
15 www.makerbuoy.com

In addition to autonomous vehicles and open-source approaches, collaboration with non-scientific platforms represents a third and powerful pillar in reducing the costs of ocean observation platforms. Mobile platforms like merchant ships, fishing vessels, ferries, cruise ships, and sailing yachts offer low-cost opportunities to host instruments across vast ocean areas, while stationary sites such as offshore infrastructures, ports, and marinas enable long-term monitoring at fixed locations. There are already several established larger programmes such as the Voluntary Observing Ship *(VOS)* scheme operating since 1853 or the international Ships of Opportunity Programme *(SOOP)* since 1980, leveraging mainly commercial vessels to collect meteorological and oceanographic data across major shipping routes, significantly enhancing global coverage and providing >90% of data for marine weather forecasts.

Collaborations with regional fishing boats equipped with sensors attached to fishing gear have supported regional monitoring such as the AdriFOOS *(Penna et al. 2023)*, FishSOOP, the Moana Project, HyFive or eMOLT that increasingly partner within the Fishing Vessels Observing Network *(FVON Ref 1)*. Cruise ships and ferries, due to their stable routes and onboard infrastructure, are ideal platforms for continuous measurements of temperature, CO_2, nutrients, and other parameters—initiatives like the European FerryBox project, the Norwegian NorSOOP or the German innovation platform Shaping an Ocean of Possibilities *(SOOP)* exemplify this.

©SeaKeepers

Additionally, private and professional sailing vessels have begun contributing real-time oceanographic and atmospheric data, including during global yacht races such as the Vendée Globe[16] and The Ocean Race[17].
These efforts are often embedded within dedicated citizen science programmes, such as Sailing for Oxygen[18], as well as initiatives led by non-profit organisations that support marine research and citizen science by using private vessels as platforms of opportunity, such as SeaKeepers[19] and Sailing4Science[20].



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16 www.vendeeglobe.org
17 www.theoceanrace.com
18 www.trans-ocean.org/sailingforoxygen
19 www.seakeepers.org
20 www.sailing4science.org

Further contributions come from purpose-built private expedition sailboats *(e.g. Apparent Winds*[21]*; Tara Ocean*[22]*; Dagmar Aaen*[23]*; Pachamama*[24]*)*, as well as from sailing vessels operated by research institutes, such as the Eugen Seibold[25] of the Max Planck Institute.

These platforms are increasingly used to sample emerging biological indicators such as environmental DNA *(eDNA)*, for example through initiatives like Citizens of the Sea[26], a partnership between Cawthron Institute and New Zealand Geographic to mobilise and equip seafarers to generate ocean data and support ocean health.

Fixed infrastructures are also increasingly involved in ocean observation, such as marinas participating in the European Marinas Network or German offshore windfarms collecting oceanographic and meteorological data within the FINO programme *(Ref 1)*. By tapping into the vast operational presence of these commercial and private maritime platforms, the oceanographic community can greatly expand observational coverage while minimizing costs, infrastructure demands, and carbon footprints.

Indeed, several large companies, at the opposite side of the marine technologies cost spectrum, have changed their attitude towards ocean observation *(IOC, 2025)*. UN Ocean Decade Corporate Data Group includes Fugro with Alcatel Submarine Networks, Ava Ocean, CGG, Equinor and Ørsted. Their determination to create frameworks and mechanisms so as to make privately owned ocean science data publicly available is now effective. This could be a threat for low cost sensor dissemination if they orientate the standards of ocean observation. It might also be an opportunity, especially for cost-effective ocean sensors depending on the outcome of the dialogue started lately *(Willis Z. et al. 2023)*.

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21 www.apparentwinds.org
22 www.fondationtaraocean.org
23 www.arved-fuchs.de
24 www.toptotop.org
25 www.mpic.de/4224334/sy-eugen-seibold
26 www.citizensofthesea.org

Cost Effective Biological Methods

Cost-effective biological monitoring methods are gaining prominence as essential tools in the framework of Essential Ocean Variables *(EOVs)*, which aim to support global ocean observing systems through the standardised collection of critical data for ecosystem assessment *(Lindstrom et al., 2012; Miloslavich et al., 2018)*.

Among these methods, low-cost technologies such as benthic cameras, when integrated with advanced computational tools like convolutional neural networks *(CNNs)*, have emerged as powerful approaches for the automated analysis of seafloor imagery *(Langenkämper et al., 2020)*. These systems enable the efficient identification and classification of benthic fauna and habitat types, minimizing the need for expensive and time-consuming manual annotation.

By applying machine learning models to image datasets, researchers can process large volumes of data collected by fixed or mobile camera systems, such as towed sleds or remotely operated vehicles *(ROVs)*, with increased speed and accuracy *(Piechaud et al., 2019)*. Moreover, the use of open-source software and hardware components can further reduce costs, making these techniques accessible for long-term ecological monitoring in data-sparse regions. These innovations align with the EOV objective of enabling scalable, repeatable, and economically viable monitoring of key marine biodiversity indicators.

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2.5. Open Source Electronics and Programming Language

Over the past decade, there has been significant progress in the development of open-source electronic platforms, characterized by accessible hardware and user-friendly software interfaces suitable for both beginners and advanced users *(Oellermann et al. 2022)*. Among these, the Arduino platform, initiated in 2003, stands out as one of the most widely adopted systems *(Banzi & Shiloh, 2022)*. The Arduino Integrated Development Environment *(IDE)* is open-source and designed to be intuitive, contributing to the formation of a large, collaborative global community comprising students, educators, hobbyists, artists, and professional engineers. This widespread community engagement has facilitated the creation of a vast array of projects, ranging from simple interactive devices to sophisticated scientific instruments *(Arduino Project Hub, n.d.)*.

The rise of online marketplaces has further supported this development by providing low-cost, modular electronic components that can be readily integrated into custom measurement systems. Such components are instrumental in democratising access to scientific instrumentation by enabling the assembly of devices with relatively good precision at a fraction of the cost of commercial equivalents *(Pearce, 2012)*.

Contemporary embedded systems exhibit several advantages that make them suitable for scientific applications. These include low cost, ease of programming, widespread adoption, and reduced development time. Depending on the required computational power and energy consumption, developers can choose between minimalist microcontroller platforms such as Arduino or Pyboard, which do not run full operating systems and can be programmed in C/C++ or MicroPython, respectively, or more powerful embedded computers like the Raspberry Pi or BeagleBone, which support full Linux distributions *(Richardson & Wallace, 2014; Upton & Halfacree, 2014)*.

Moreover, the availability of integrated circuits originally designed for portable medical or consumer electronics applications has led to new opportunities in sensor signal conditioning and analog-to-digital conversion. These circuits combine low cost with high performance, enabling edge computing, i.e., the processing of data close to the source *(sensor)*, a paradigm increasingly adopted in scientific instrumentation for reducing latency and bandwidth demands *(Shi et al., 2016)*.

In conclusion, the combination of open-source hardware, low-cost components, and embedded computing platforms has enabled a new era of accessible, modular, and precise scientific instrumentation development.

2.6. Data Transmission Technologies and the Coastal Ocean of Things (COOT)

Wireless communication is a critical component in COOT devices, as it allows the user to receive the data remotely, without needing to physically retrieve all the sensors. Several technologies exist to achieve this wireless data transmission, depending on the user's needs *(Mishra et al. 2023)*. The most widely used technologies are Sigfox, LoRa/LoRaWAN, Narrow Band IoT *(NB-IoT)* and LTE-M, and satellites *(Mekki et al., 2018; Cocker et al., 2022)*. The main differences between the different technologies are *(i)* cost, *(ii)* communication range, *(iii)* data rate, *(iv)* power usage, and *(v)* network coverage.

Sigfox uses Ultra Narrowband *(UNB)* modulation to transmit data to proprietary base stations deployed in over 70 countries *(Mariani et al., 2021)* in the sub-GHz unlicensed bands *(e.g. 868 MHz in Europe and 915 MHz in North America (Mekki at al., 2018)*. End devices use DBPSK modulation for uplink and GFSK modulation for downlink in a 100 Hz band *(or 600 in some regions) (Koepp et al., 2018)* providing a maximum data rate of 100 bps. This UNB allows Sigfox to be subject to less noise, leading to the reduction of required transmitting power. Uplink messages are limited to 140 messages per day per device, with a maximum message length of 12 bytes, thus limiting the maximum data that each device can transmit per day to only 1680 bytes. Just like LoRaWAN and NB-IoT, Sigfox requires a base station nearby for the device to transmit to, with one device sending data to only one base station.

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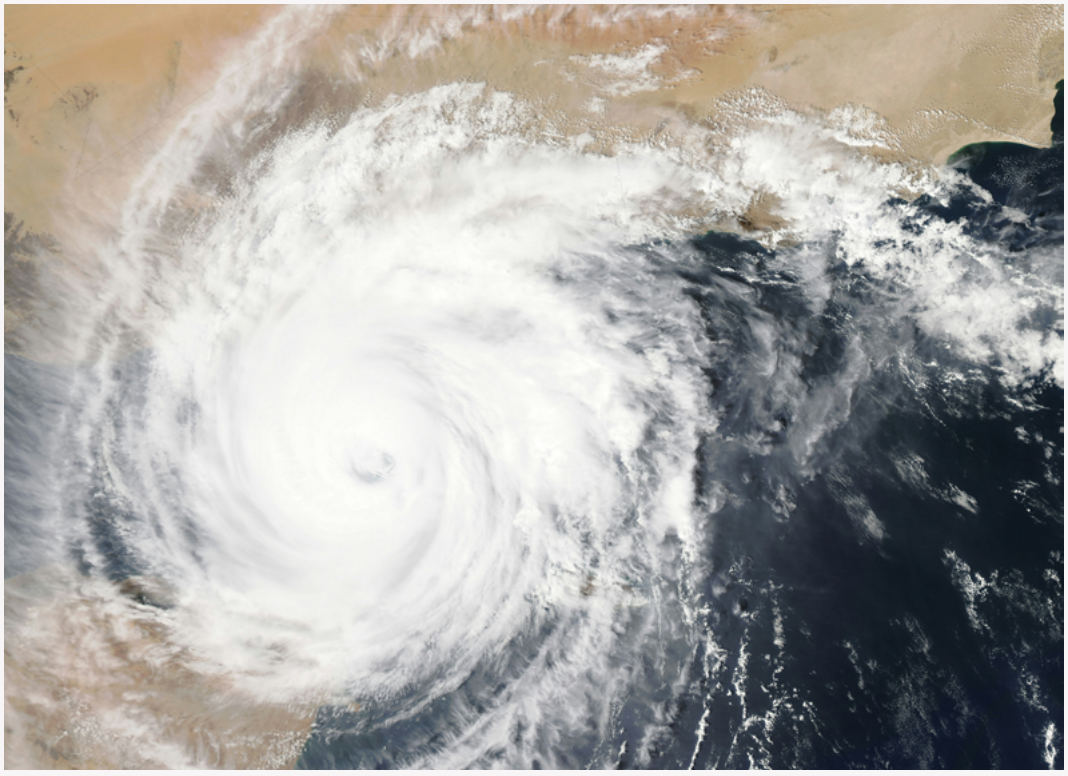
LoRa is a patented Chirp Spread Spectrum *(CSS)* technology used as the physical layer in the LoRaWAN protocol. Just like Sigfox it operates in the unlicensed sub-GHz spectrum *(e.g. 433 MHz and 868 MHz for Europe and 915 MHz for North America)*, but unlike Sigfox, LoRaWAN uses 250 or 500 kHz bands *(depending on the region) (Sanchez-Iborra et al., 2016)*, resulting in data rates between 300 bps and 50 kbps. The high variability in data rate is also due to something LoRa calls Spreading Factor *(SF)*, a measure of how long it takes the chirp to spread the entire bandwidth. SF can vary between 7 and 12 and are either manually selected by the user or automatically selected depending on the link quality between base station and device. Higher SFs increase reliability at the cost of data rate. Unlike Sigfox, LoRaWAN gateways can be purchased to increase network coverage *(Marcelli et al. 2021)*, additionally, LoRaWAN devices send messages to all nearby gateways, thus increasing reliability.

NB-IoT and LTE-M are two protocols developed by the 3rd Generation Partnership Project *(3GPP)* for IoT devices. The main advantage compared to LoRaWAN and Sigfox is that they operate in a protected part of the spectrum and should therefore be less prone to interference. This, however, requires that the local carrier has adopted this standard. NB-IoT occupies a frequency bandwidth of 180-200 kHz, while LTE-M uses 1.4-20 MHz bandwidth. This results in NB-IoT using less power at the expense of a significantly reduced data rate of 26-127 kbps, depending on the version *(Wang et al., 2017)*.



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Satellite transmitters/transceivers can also be used for wireless data communication. These devices can be especially useful when monitoring parts of the ocean that are not near a coast, as they communicate directly to satellites. When selecting a satellite provider, it is important to know the constellation configuration, or how many satellites are placed in what orbits. Geostationary *(GEO)* satellites can provide near-global coverage with only 3 satellites, at the cost of high latency and high transmission power requirements, while low-Earth orbit *(LEO)* satellites require less transmission power and have lower latency, at the cost of needing more satellites. There are several companies that offer Direct to Satellite *(DtS)* modems designed for IoT devices, with five major players: Inmarsat[27] *(GEO)*, Iridium[28] *(LEO)*, Eutelsat[29] *(GEO)*, Globalstar[30] *(LEO)*, and Thuraya[31] *(GEO) (Centenaro et al., 2021)*.

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28 www.iridium.com
29 www.eutelsat.com
30 www.globalstar.com/en-us/products/iot
31 www.thuraya.com

3. Applications of Low-Cost Sensors in Observing Systems

3.1. Contribution of Low-cost Technologies to Coastal Observation

Low-cost sensors enable comprehensive monitoring of sediment transport, hydrodynamic patterns, and shoreline dynamics, providing high-resolution, real-time data critical for understanding and managing coastal systems *(Albaladejo et al., 2021)*. These observations are essential for assessing the impacts of sea-level rise *(Campagnaro et al., 2024)*, coastal erosion, and storm surge events on vulnerable communities and infrastructure *(Álvarez-Silva et al., 2023; Briciu-Burghina et al., 2023)*. For instance, sensors deployed along shorelines can monitor changes in sediment deposition and erosion, allowing for predictive modeling of shoreline retreat and its implications for coastal habitats and human settlements *(Green et al., 2019; Adade et al., 2021)*. Global change drivers, such as climate change, population growth, and coastal urbanization, exacerbate the pressures on coastal systems, highlighting the need for precise and continuous observations *(Cavanaugh et al., 2024)*, in order to understand and to describe the complex interactions between climate stressors and local coastal processes. For example, rising sea levels, driven by global warming, increase the frequency and severity of flooding in low-lying areas, necessitating advanced monitoring tools to predict and mitigate risks. Coastal urbanization often leads to habitat degradation, making it vital to track anthropogenic impacts like increased sedimentation and pollution caused by runoff.

Continuous monitoring also informs the design of adaptive coastal defense mechanisms, such as living shorelines, which integrate natural features like marshes and oyster reefs with engineered structures to reduce wave energy and prevent erosion. Similarly, low-cost sensors can support managed retreat strategies by providing detailed datasets that identify areas at highest risk and prioritize relocation efforts. These approaches enhance resilience by integrating scientific insights into policy and infrastructure development.

Localized observations generated by low-cost technologies enhance our understanding of nearshore dynamics, including wave energy distribution, sediment transport pathways, and nutrient fluxes *(Rosa et al. 2021)*. For example, sensors deployed in estuarine environments can track how tidal flows influence sediment and nutrient distribution, which is critical for the health of seagrass beds and mangrove ecosystems. These insights inform sustainable development planning, ensuring that the construction of ports, breakwaters, and other coastal infrastructure aligns with environmental conservation goals. Moreover, low-cost sensors contribute to monitoring anthropogenic impacts, such as pollution from agricultural runoff or industrial discharges. By measuring water quality parameters *(Murphy et al., 2015)* like turbidity *(Parra et al., 2023; Matos et al., 2019; Gillett et al., 2019)*, nutrient concentrations, and dissolved oxygen, these sensors provide early warnings of environmental stressors, enabling timely mitigation actions. This capability is especially vital for protecting marine protected areas *(MPAs)* and biodiversity hotspots, where maintaining ecological balance is crucial.

The scalability and affordability of low-cost sensors also facilitate the establishment of community-based monitoring programmes. In these initiatives, local stakeholders are trained to deploy and maintain sensors, empowering them to participate in data collection and management actively. These programmes not only enhance observational coverage but also promote Ocean Literacy and a sense of stewardship among coastal populations.

Low-cost sensor technologies are revolutionizing coastal observations by providing accessible, high-quality data that supports science-based decision-making. Their integration into coastal management frameworks ensures a holistic approach to addressing environmental challenges while promoting sustainable development and community resilience. The ability to monitor and respond to global change drivers makes these technologies indispensable for safeguarding the future of coastal ecosystems and the communities that depend on them.

3.2. Open Ocean Applications

The Voluntary Observing Ship *(VOS)* programme and the Ship of Opportunity Programme *(SOOP)* are critical components of GOOS, contributing to long-term, large-scale oceanographic and meteorological data collection. The VOS programme, coordinated by the World Meteorological Organization *(WMO)*, enlists commercial and research vessels to report meteorological parameters such as sea surface temperature *(SST)*, air pressure, wind speed, and cloud cover. These data are essential for weather forecasting, climate research, and ocean modeling *(WMO, 2011)*.

Complementing the VOS, the SOOP focuses on deploying automated instruments from ships, particularly along repeated routes. One key instrument used in SOOP is the eXpendable BathyThermograph *(XBT)*, which profiles upper-ocean temperature and thermocline structure, enabling researchers to monitor ocean heat content and variability *(Slovan et al., 2018)*. Unlike dedicated research vessels, SOOP ships operate on regular commercial routes, offering cost-effective and frequent sampling of the upper ocean.

Together, these programmes enhance global ocean coverage, especially in under-sampled regions such as the Southern Ocean and remote Pacific areas. They provide essential baseline data for validating satellite observations and supporting climate change assessments *(Newman et al., 2019)*.

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3.3. Deepsea Applications

Deep seas *(under 200 m water depth)* include most of the sea water volume of our planet. It is the least observed, but largest habitat *(Levin et al.,2019)*. It was first explored with expeditionary methods using research vessels. The UN Ocean Decade objectives are opening the minds for better cooperation between coastal and deep-sea specialists. The communities have been involved in the European Research Area, following the regional GOOS community building efforts. Indeed, depending on the neighbouring seas, some observation institutions are more experienced in deep sea *(MonGOOS)* others to shallow water *(NOOS – the North-West-Shelf Operational Oceanographic System of EuroGOOS)*.

In deep seas, satellite positioning and data transmission use are not possible or limited to a few monitoring sites where buoys or ships are relaying the signals at air-sea interface. Maps are expensive to establish in deep seas. Positioning, transmission and mapping, together with water column current description are requiring underwater acoustic technologies. In situ observation also needs accurate sensors because of the limited variability of the EOVs at depth *(except for geohazards and accidental pollution which are requiring instruments with broader ranges)*. The main difference with shallow water observation technologies is the hydrostatic pressure. Pressure housings and deep sea connectors are costly; some sensor transduction components are requiring very specific integration such as getting rid of air or void bubbles; several technologies have an intrinsic depth limit anyway.

Nevertheless, many developments of low cost instruments are relevant for deep sea use. On fixed point observatories for instance, the extension of parameters measured *(Contreira-Pereira et al., 2013)* and the spatial coverage on the seafloor *(EMSO Azores)* or through additional low cost moorings is a common practice. Small and low cost Animal Borne Ocean Sensors *(McMahon et al., 2021)* are withstanding the pressure at depths reached by Kergelen islands elephant seals *(i.e. 1,000 m water depth)* and designed for 2000 m water depth.

A special effort must be undertaken on the use of components under equilibrated pressure. Oil filled hoses with common electrical and optical wires components inside are already used by underwater vehicles to cut weight and cost. The compressibility and thermal expansion must be calculated to design a compensation bladder. The qualification of electronic components to extend this design to any equipment is unfortunately very limited and neither shared between private nor public underwater engineering design teams. The sharing of qualified « pressure tolerant electronic systems » *(Bingham N., 2013)* is a frontier to address to extend low cost instrumentation to deep sea. Cutting the costs of acoustic equipment is another priority. The EOOS Technology Forum *(EuroGOOS, 2025)* showed the will to include deep sea in the low cost sensor approach of several key players such as: Synchro initiative, 3D printed and oil filled containers *(Motsenbocker et al., 2024)* or video systems *(Dominguez-Carrió et al., 2021)*.

3.4. Environmental Monitoring and Marine Conservation

Environmental monitoring is an indispensable tool for ensuring the health and sustainability of marine and coastal ecosystems. By integrating data from diverse sources and leveraging tools like environmental indicators and marine monitoring services, countries can develop and implement effective policies that address both local and global environmental challenges *(Vasil Simeonov, 2019)*. The continued use of high-quality, accessible, and regularly updated data ensures that decision-making is informed and effective, supporting long-term sustainability in oceans and coastal areas. Environmental monitoring is fundamental to evaluate environmental conditions and trends, to support the development and implementation of policies, and to provide essential data for reporting to national policymakers, international bodies, and the public.

Therefore, there is a necessity to implement adequate monitoring programmes, efficient data and information management systems, best practices for the development of standardised environmental indicators, structured services and assessment and reporting methods *(United Nations Economic Commission for Europe – UNECE)*. The objective is to achieve the integration of relevant and easily accessible information, as well as consistent and systematic data on the physical state and dynamics of the ocean and marine ecosystems, both on a global scale and within European regional seas.

These systems could generate a variety of products, including real time observed data, forecasts, time series, and calculations for important oceanographic parameters and products to support marine and maritime applications, including monitoring eutrophication and generating boundary conditions for small-scale hydrodynamic models used in coastal zone management, and to contribute to several EU policies related to marine safety, coastal management, marine resources *(marine.copernicus.eu)*.

The services should provide freely accessible, scientifically validated, and regularly updated data on the physical and biogeochemical conditions of the global ocean and regional seas, offering comprehensive insights into oceanographic parameters, such as currents, temperature, wind patterns, salinity, sea level, sea ice, and biogeochemistry. The utilization of this data is likely to be of **significant interest to a wide range of stakeholders**, including vessel traffic services, search and rescue operations, oil spill response teams, offshore platforms and the renewable energy industry. Furthermore, long-term data series are fundamental for understanding and addressing climate change and its impact *(such as sea level and ocean temperature)*, for enhancing weather forecasting, and seasonality.

By providing comprehensive insights for policy analysis and decision-making, environmental monitoring should ensure high-quality, comparable information that should be accessible to all stakeholders involved in environmental monitoring. A standardised approach to data collection and assessment, along with the use of shared indicators, facilitates international collaboration, enabling countries to learn from one another and coordinate responses to global challenges, also driving research and leading to the development of improved and shared policies.

To implement the EU Integrated Maritime Policy and support the Marine Strategy Framework Directive and the Maritime Spatial Planning Directive, European Member States are required to improve marine monitoring and design monitoring networks. However, traditional methods have low spatial and temporal resolution and can be very expensive. This can be addressed by developing and testing innovative and cost-effective monitoring systems *(Danovaro et al., 2016)*.

Affordable technologies facilitate real-time monitoring of key environmental parameters *(Lockridge et al. 2016)*, including water temperature, salinity, dissolved oxygen, and nutrient levels. Such data are critical for identifying stressors to marine ecosystems, such as eutrophication, hypoxia, and harmful algal blooms *(HABs)*. For example, low-cost optical sensors can measure chlorophyll concentrations, providing early warnings of algal blooms that could disrupt fisheries and aquaculture operations. These real-time detection systems powered by low-cost sensors enable rapid responses to environmental threats, reducing the potential for long-term damage to ecosystems.

Low-cost technologies also **enhance the management of Marine Protected Areas (MPAs) by providing data on habitat usage, species behavior, and environmental variability**. For instance, underwater acoustic sensors can monitor the presence of endangered marine mammals, helping to enforce conservation regulations and guide shipping routes to minimize collisions. Similarly, cost-effective imaging systems can document changes in coral reef health, identifying bleaching events or algal overgrowth that signal ecological stress. These tools are vital for evaluating the effectiveness of conservation interventions, such as habitat restoration projects, and for guiding adaptive management strategies.

Furthermore, low-cost platforms enable long-term monitoring in remote and resource-limited MPAs where traditional systems may be financially unfeasible. These technologies, such as low-power telemetry systems, can transmit critical data on water quality, temperature gradients, and biodiversity indices to central databases, fostering global collaboration in marine conservation. By lowering the entry barrier to advanced monitoring capabilities, affordable technologies ensure that MPAs in developing regions are equipped to meet conservation goals and respond to global change drivers, such as climate-induced shifts in species distributions.

3.5. Supporting Fisheries and Aquaculture

The EU Common Fisheries Policy aims to implement the ecosystem-based approach to fisheries management so as to ensure that negative impacts of fishing activities on the marine ecosystem are minimized, and to ensure that aquaculture and fisheries activities avoid the degradation of the marine environment. It is known that fish distribution and stock size are related to environmental parameters variation in time and space *(e.g., temperature, salinity, oxygen and chlorophyll)*, with consequent influence on fisheries sustainability and economy. Therefore, the integration of environmental conditions into species abundance and distribution models allows for an increased understanding of the influence of environmental drivers and climate change on their distribution, abundance and exploitation status *(Carpi et al., 2015; Chiarini et al., 2022)*. The importance of sensor-based observations, to directly measure parameters in the field, in order to improve ecosystem approach to management is already well known and documented *(e.g. Kröger et al. 2009; Schmidt et al. 2019; Aguzzi et al., 2022)*.

Fisheries observing systems based on the use of oceanographic class sensors on fishing vessels and/or fishing gears already **proved to be useful not only to feed oceanographic models and expanding knowledge on climate change** *(e.g. Aydoğdu et al. 2016; Kerry et al. 2024)* but also to improve the ecosystem approach to fisheries management *(Manning and Pelletier 2009; Carpi et al. 2015; Russo et al. 2015, 2016; Lucchetti et al. 2018; Hirose et al. 2024)*.

The technology available for this type of application is constantly evolving and the number of EOVs that can be monitored with this approach is increasing *(Martinelli et al. 2016, 2017, 2023, 2024; Patti et al, 2016; Hirose et al. 2024; Jakoboski et al. 2024)*. Furthermore, novel Aquaculture Observing Systems approaches involving simultaneous use of sensor deployments and FerryBox systems in coastal regions and the development of real-time event detection systems, are being developed in recent EU projects *(Martinelli et al. 2023b, 2024)*. In fisheries, low-cost sensors monitor oceanographic conditions that influence fish stock dynamics, such as sea surface temperature, chlorophyll concentration, and salinity gradients *(Schmidt et al., 2018)*. These data support the development of sustainable fisheries management plans by informing quota settings, seasonal closures, and habitat protection measures. For example, temperature sensors integrated with GPS-enabled drifters can map thermal fronts where fish are likely to aggregate, providing valuable insights for both commercial and artisanal fisheries.

In aquaculture, sensor networks improve operational efficiency and environmental sustainability. Continuous monitoring of dissolved oxygen and pH/pCO2 levels ensures optimal conditions for fish health, reducing the risk of disease outbreaks and mortality. Low-cost ammonia sensors, for instance, can detect harmful buildup of waste products in real time, allowing farmers to adjust feeding regimes or aeration strategies promptly.

Integrated monitoring systems can also track nutrient inputs and waste outputs, helping to mitigate the environmental impacts of aquaculture operations. For example, sensors capable of measuring nitrate and phosphate concentrations can ensure that effluent discharges remain within permissible limits, protecting surrounding ecosystems. Additionally, advanced low-cost imaging technologies can monitor fish growth and behavior, providing data that optimize feed utilization and reduce waste, thus enhancing production efficiency.

It is also worth mentioning that upwelling is an important process that impacts water quality, aquaculture production and the recruitment of commercial fish species in coastal areas. Cost-effective ocean sensors like High Frequency Radars can be used for direct upwelling monitoring over coastal areas. Significant efforts have been recently devoted to the quantification of the intensity, duration, and spatio-temporal variability of this phenomenon by means of 2D maps of coastal upwelling index *(CUI)*, generated from remotely sensed hourly surface current observations provided by High-Frequency Radars *(Lorente et al., 2023)*. This approach offers a complementary insight into the diverse CUIs derived from historical estimations of other met-ocean parameters *(e.g. wind, sea level pressure, or sea surface temperature)* to indirectly infer seasonal trends of upwelling along the shoreline *(González-Nuevo et al., 2014)*.

These technologies are particularly transformative for **small-scale and artisanal aquaculture enterprises**, which often lack access to advanced monitoring tools. By reducing operational costs and increasing yield predictability, low-cost sensor networks contribute to the economic viability and resilience of these businesses. Moreover, data collected from aquaculture monitoring systems can be i**ntegrated into regional marine management frameworks**, fostering collaboration between aquaculture operators, fisheries managers, and conservationists to ensure that economic growth aligns with environmental stewardship.

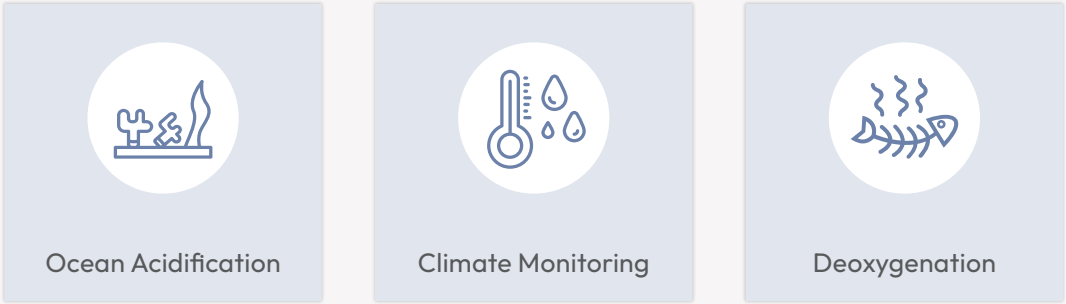
3.6. Climate Change Research and Ocean Health

By enhancing spatial and temporal data resolution, affordable technologies contribute significantly to our understanding of climate-induced changes in oceanic systems. Low-cost sensors are integral to monitoring ocean acidification, a critical consequence of increased atmospheric CO_2 levels. These sensors provide continuous, high-resolution measurements of pH, carbonate chemistry, and alkalinity, enabling researchers to track acidification trends and assess their impacts on calcifying organisms, such as corals, shellfish, and planktonic species. The ability to deploy these sensors widely and in previously under-monitored regions has expanded the scope of acidification studies, offering insights into regional variability and localized stressors.

In addition, cost-effective temperature sensors deployed across diverse marine environments are essential for detecting and analyzing marine heatwaves. These episodic events have devastating effects on coral reefs, kelp forests, and other sensitive ecosystems, causing widespread habitat loss and biodiversity declines. By enabling the collection of temperature data in near real-time, these sensors support the development of early warning systems that inform conservation and restoration strategies.

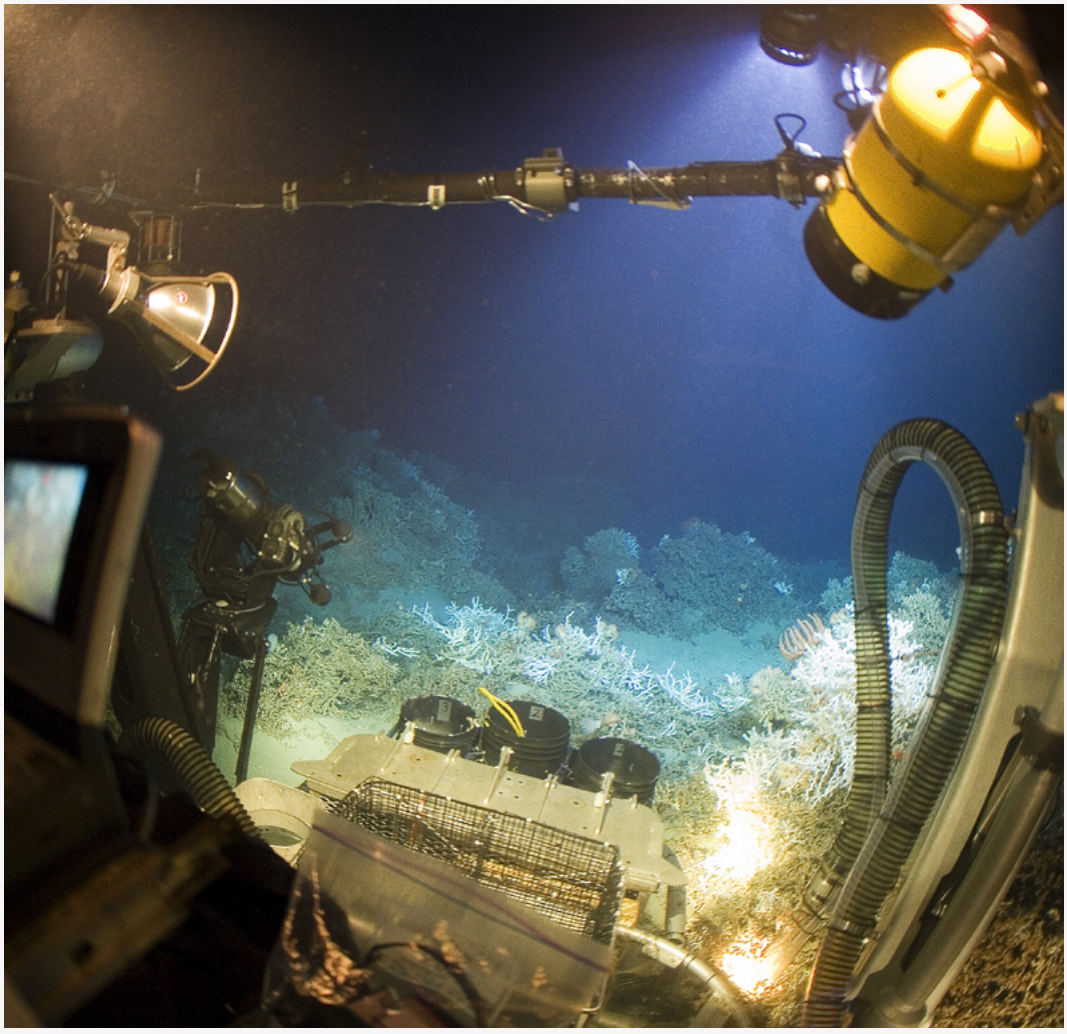
Low-cost oxygen sensors are equally important for studying deoxygenation, another critical stressor linked to climate change. Deoxygenation threatens marine organisms and ecosystems by reducing habitable zones and altering food web dynamics. Deploying affordable oxygen sensors in hypoxic zones, such as coastal dead zones and oxygen minimum layers, provides critical data for understanding the extent and drivers of oxygen depletion. These observations are crucial for developing mitigation strategies to preserve marine biodiversity and maintain ecosystem services.

The integration of data from these sensors into global databases, such as the Global Ocean Acidification Observing Network *(GOA-ON)* and the World Ocean Database, supports the development of Earth system models. These models predict future climate scenarios, assess the cascading effects of oceanic changes on global systems, and guide mitigation and adaptation strategies. By improving the resolution and accuracy of these models, low-cost technologies play a pivotal role in advancing climate science and policy.



Furthermore, accessible technologies enable broader participation in climate change research, empowering underrepresented regions to contribute valuable data to the global scientific community. For example, community-based monitoring programmes in small island developing states *(SIDS)* utilize low-cost sensors to document localized impacts of sea-level rise, acidification, and temperature shifts. These contributions not only fill critical data gaps but also ensure that the perspectives and priorities of vulnerable communities are reflected in global climate strategies.

Affordable marine observation technologies are **indispensable for advancing our understanding of climate change and its impacts on ocean health**. By democratising access to scientific tools and fostering international collaboration, these technologies contribute to a more equitable and comprehensive approach to addressing one of the most pressing challenges of our time.



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4. Benefits and Advantages of Low-Cost Sensors

A SWOT analysis *(Figure on the next page)* has been conducted to identify, in a summarized way, the main benefits of low-cost ocean networks and uncover future opportunities.

Low-cost sensors and technologies in marine observations offer significant strengths, including cost-effectiveness, scalability, increased spatial and temporal coverage, empowerment of Citizen Science, and improved data accessibility. However, they face weaknesses such as challenges in calibration and accuracy, durability in harsh environments, reliable data transmission, and lack of standardisation.

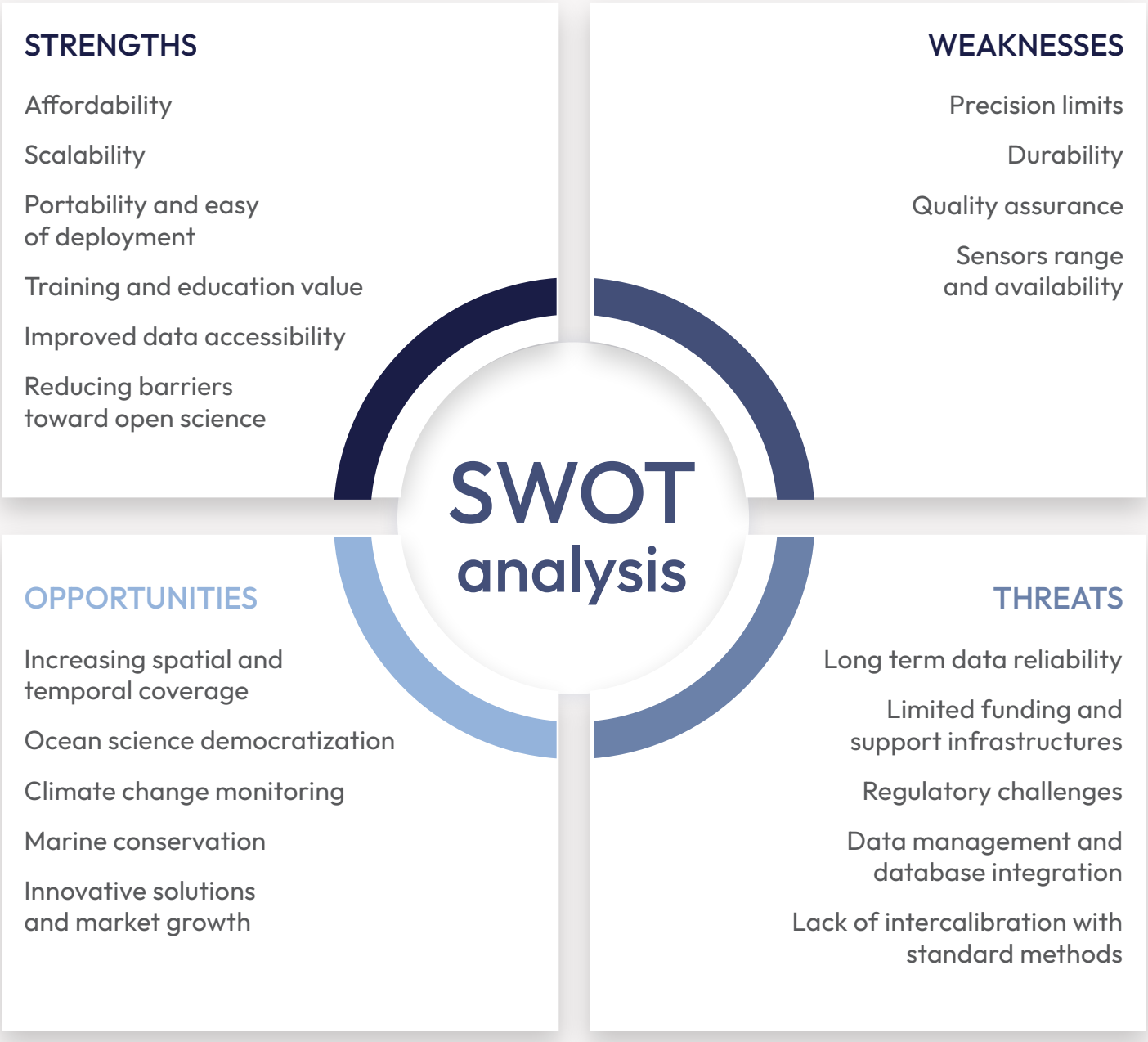
Opportunities for these technologies include advancements in sensor design, integration of AI and machine learning, global collaboration, educational initiatives, and policy support. On the other hand, threats include environmental conditions, market competition, regulatory barriers, and data security concerns.

This SWOT analysis provides a comprehensive overview of the potential benefits and challenges associated with implementing low-cost ocean sensors, offering insights for strategic planning and decision-making in advancing marine observations.

A foundational concept underpinning the SWOT analysis is collaborative development, which emphasizes the integration of diverse stakeholders in the pursuit of shared objectives. In particular, this approach fosters technological research aimed at developing low-cost instrumentation, facilitating broader access to oceanographic data collection.

The emerging synergy between ocean scientists, technology research institutions, small and medium-sized enterprises *(SMEs)*, large-scale research infrastructures, and non-profit organisations engaged in Citizen Science represents a promising opportunity. This multidimensional collaboration can **accelerate innovation, democratize data acquisition, and enhance the overall effectiveness of ocean observation systems**.

Figure 6: SWOT analysis of sustainable low-cost ocean sensors



4.1. Cost-Effectiveness and Scalability

Low-cost sensors offer unparalleled affordability without compromising the quality of data they provide. By significantly reducing the financial barriers to entry, these technologies facilitate the establishment of widespread observation networks, including in regions with limited resources *(Rabello et al., 2021)* and thereby covering larger areas that previously were unobserved. Their scalability is evident in their adaptability to various environments and objectives, ranging from small-scale community monitoring projects to large-scale international collaborations *(Mariani et al., 2021; Wang et al., 2021)*.

An important aspect of scalability is the modular design, both in terms of hardware and software, of many low-cost sensors. Modular systems enable users to tailor sensor configurations to integrate with various observing platforms and observing modes, and to meet specific requirements, optimizing data collection while minimizing waste and redundancy. This results in improved scalability of the manufacturing process and reduced per-unit costs. This customization makes them suitable for diverse applications, including water quality assessment, biodiversity monitoring, and climate change research. Furthermore, the affordability of these systems allows for redundancy in deployment, ensuring data continuity even in the event of device failures.

On the other hand, an additional advantage would lie on the minimal environmental impact due to the use of eco-friendly materials, sustainable designs and energy-efficient technologies, aligning with global sustainability goals.

4.2. Increased Spatial and Temporal Coverage

Despite the increasing wealth of observations from satellites, floats, moorings, and ships, observational coverage is still sparse for vast parts of the deeper ocean, especially on the ubiquitous mesoscale. With the growing exploitation of the seas, mesoscale prediction of ocean physical parameters and, more recently, their biophysical variability have been key goals of the ocean forecasting community. Ocean models evolve according to physical and dynamical constraints. They have the ability to produce forecasts using information on the atmospheric surface forcing, the ocean's bathymetry, and the recent state of the ocean obtained from ocean observations and introduced into the model through data assimilation. Ocean modelling is an active field and new knowledge stemming from observations and theoretical studies produces a continuous stream of improvements to ocean models, which leads to more accurate ocean analyses and forecasts *(Davidson, 2019)*. The discontinuous spatio-temporal sampling of observations could have a strong impact when using them to construct climatologies or evaluate models. The advent and deployment of new observing systems *(e.g., HF radars, gliders, and low-cost buoys)* will provide the necessary in situ observations density, at least on a regional scale. The affordability and ease of deployment of low-cost sensors, in fact, enable researchers to expand observational coverage to previously under-monitored areas *(Nalakurthi et al., 2024; Trevathan et al., 2021)*, and to intensify monitoring in highly critical areas. This

includes remote regions, such as polar environments and deep-sea ecosystems, as well as densely populated coastal zones where anthropogenic pressures are most pronounced. Increased spatial coverage provides a more comprehensive understanding of oceanographic phenomena, allowing researchers to identify patterns and anomalies that might otherwise go unnoticed.

Temporal coverage is equally enhanced by low-cost technologies. Continuous monitoring made possible by durable, energy-efficient sensors provides real-time data streams, enabling the detection of short-term events, such as algal blooms or storm surges. Long-term deployments *(Beddows et al., 2018)*, supported by advancements in power management and data transmission, contribute to time-series datasets essential for understanding seasonal and decadal trends. These datasets are invaluable for validating predictive models and informing adaptive management strategies.

To further increase observation network capability, a key point is the evolution of low-cost, efficient observing systems with minimal operating costs and integrating them with the existing ones. This can be achieved by generating standardised observation-based validation metrics *(Ryan et al., 2015)* from all available forecast system outputs, as well as by promoting intercomparison among different forecast systems and their respective forecast skills, in order to support the continuous improvement of these systems *(Davidson et al., 2019)*.

4.3. Empowering Citizen Science Initiatives

Citizen participation in marine data collection presents both opportunities and challenges that are closely linked to the potential of crowdsourcing. This approach offers substantial benefits for expanding observational coverage, particularly in coastal regions where contributions from large numbers of participants can be obtained with comparatively low effort *(French et al. 2017)*. Contributors may include members of the general public as well as organized groups such as fishers, divers, and aquaculture operators. While engaged in their routine activities, participants can seamlessly collect data either through personal devices, such as smartwatches, smartphones, or other wearables equipped with miniature sensors, or through custom-built infrastructure, such as low-cost *"black boxes"* installed on vessels to perform autonomous measurements from platforms of opportunity.

The collected data are transmitted to distributed networks of harvesting nodes, where they are synthesized, integrated, and assembled into updated information about the marine environment. In this way, crowdsourcing expands data acquisition beyond traditional, resource-intensive platforms, generating more comprehensive datasets that can support scientific research, resource management, and marine conservation. A wide range of contributors, including recreational boaters, sailors, divers, swimmers, and marine enthusiasts, in addition to institutional actors such as fish farmers, ports managers, and coastguards, can provide valuable observations while conducting their daily activities.

Smartphone applications and embedded sensors in personal devices can be used to record parameters such as sea level, surface temperature, water quality, and marine debris. Dedicated acquisition systems equipped with multiple sensors may also transmit measurements via satellite or GSM networks from platforms of opportunity to onshore cloud servers. Beyond expanding observational coverage, crowdsourcing also strengthens public engagement with the marine environment, fostering awareness of its significance and associated challenges. Furthermore, large-scale datasets generated by citizens have the potential to enhance the accuracy and predictive skill of oceanographic models.

Nonetheless, the issue of data quality is central to the effective use of crowdsourced marine observations. Such systems must account for errors caused by miscalibration, malfunction, or inaccuracy, thereby requiring the development of advanced validation strategies. These may include statistical comparisons with expert-collected baseline datasets or model outputs, AI-enabled assessments involving the intercomparison of data streams and automated detection of faulty inputs, and consensus-based approaches for filtering unreliable observations.

Several challenges to validation remain. The quality and bias of crowdsourced data are expected to vary considerably, influenced by factors such as sensor heterogeneity, inconsistent reporting, or misuse. Comparisons with baseline datasets may be constrained by mismatches in spatial or temporal resolution. Moreover, citizen contributors may lack the scientific knowledge or technical rigor necessary to ensure accuracy.

Addressing these challenges will require the evolution of validation methodologies. Potential improvements include the systematic use of quantitative metrics to evaluate citizen-collected data against professional datasets, the integration of alternative sources such as numerical models to assess accuracy where expert data are unavailable, and the implementation of enhanced automated checks for data formatting, consistency, and plausibility. In addition, validation efforts should incorporate assessments of contributor reliability and metadata quality.

Despite progress in automation, manual interventions by expert curators will remain indispensable. Quality assurance will continue to depend on established protocols and guidelines, complemented by direct interaction and feedback between experts and contributors.

Low-cost sensors have revolutionized the role of Citizen Science in marine research by making data collection tools accessible to non-specialists. Community-led monitoring programmes, equipped with user-friendly devices, allow local stakeholders to contribute to scientific datasets while gaining a deeper understanding of their marine environments. This democratisation of science fosters a sense of ownership and stewardship among participants, encouraging sustainable practices and conservation efforts.

Successful Citizen Science initiatives have utilized various low-cost technologies to engage communities in projects covering various topics or themes such as biology and ecosystems, physics, biogeochemistry, marine pollution and other cross disciplinary topics. Notable examples include FVON[32] and affiliated projects employing low-cost sensors to monitor subsurface temperature in partnership with fishing communities worldwide. Recreational divers use low-cost cameras and sensors to document coral reef health[33]. In some initiatives e.g., CITCLOPS, EyeOnWater[34], coastal residents measure water quality parameters to track pollution sources using smartphones, Secchi disks and other low-cost technologies. These efforts not only augment professional research but also provide unique, localized insights that might be overlooked in broader studies. By integrating citizen-generated data into scientific databases, researchers can benefit from enhanced spatial and temporal coverage while promoting public engagement in marine science.

First, Citizen Science observations would provide a prediction validation mechanism at the end-user location of interest and, second, they would enhance ocean forecast initial conditions. These efforts will be facilitated by the rapid growth in wireless communication capabilities and mobile computing platforms, such as smartphones.

One way to implement and improve the observing system is to encourage end-users of forecast information to collect and contribute ocean observations from both marine platforms *(e.g., fishing vessels, sailboats)* and land-based platforms *(e.g., piers, docks)* on a best-effort basis. When done consistently and with quality control, these contributions can effectively complement existing forecast systems *(Merlino et al. 2021, 2023a; Giugliano et al. 2025.)*

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32 www.fvon.org
33 www.reefcheck.org
34 www.eyeonwater.org

4.4. Improved Data Accessibility and Open Science

The integration of low-cost sensors into open-access platforms has transformed data accessibility in marine research. By lowering the cost of data acquisition, these technologies facilitate the sharing of information across institutions, disciplines, and geographic boundaries. Open science initiatives, supported by accessible technologies, promote transparency, reproducibility, and collaboration, accelerating scientific discovery and innovation.

Improved data accessibility has significant implications for policy and management. Decision-makers can leverage openly available datasets to design evidence-based strategies for marine conservation, resource management, and climate adaptation. Furthermore, accessible data empower marginalized communities to advocate for their environmental and economic interests, fostering more inclusive and equitable governance.

4.5. Support to Operational Oceanography

Operational oceanography, often described as the oceanic counterpart to weather forecasting, provides estimates of key ocean variables, such as sea level, temperature, currents, and surface height, for the past, present, and future. It is defined as the sustained provision of routine oceanographic information necessary for informed decision-making *(Davidson et al., 2019)*.

According to some authors, in any case, the model that assimilates traditional satellite-derived surface observations and subsurface data from Argo floats still fails to represent the complexities of the subsurface flow, which are revealed by the fishing-vessel data *(Lago et al. 2025)*.

At the heart of operational oceanographic systems lies a synergy between several interdependent components: a multi-platform observational network, a robust data management system, data-assimilative numerical prediction models, and an effective dissemination system. Together, these elements form an integrated mechanism capable of delivering a comprehensive picture of ocean conditions across different timeframes.

Ocean observations are essential to every facet of operational oceanography. They not only provide data for assimilation into models but also play a critical role in the research cycle, and in the verification and validation of forecast products *(Davidson et al., 2019)*.

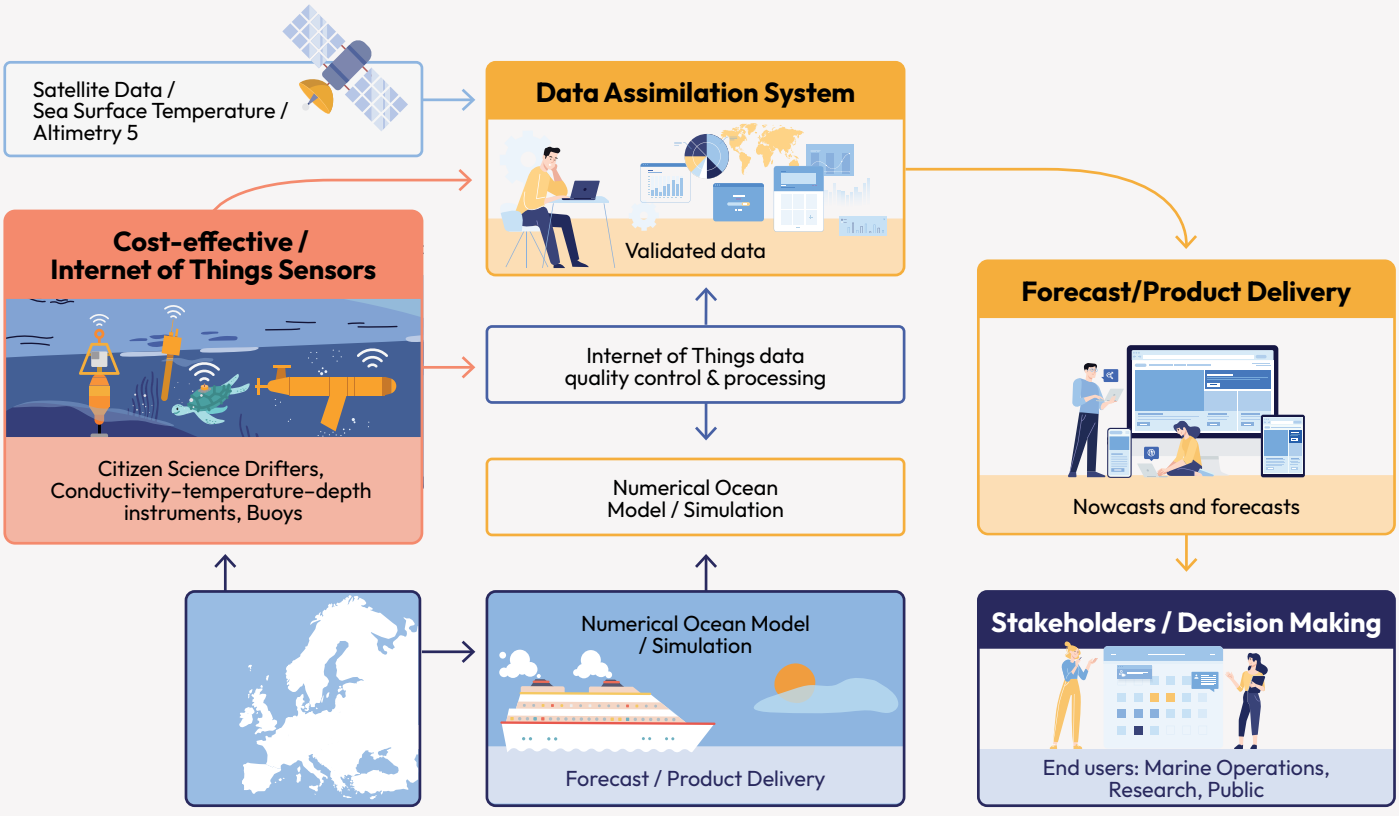
The forecasting process relies heavily on near real-time collection of observational data, which is assimilated into numerical models to refine the initial conditions used for ocean predictions *(Schiller et al., 2018)*. The strength of operational oceanography, therefore, lies in the continuous interaction between prediction and observation systems, a dynamic that ensures the accuracy and reliability of the services provided.

Today, operational oceanography systems are capable of delivering routine, fully supported oceanographic information across global to coastal marine environments.

These systems encompass not only physical oceanographic variables but increasingly include biogeochemical parameters, with ongoing research aiming to integrate ecosystem forecasting. Operational oceanography serves a wide range of stakeholders, including marine industries, service providers, government agencies, and research and development *(R&D)* organisations.

Within this context, low-cost sensors are becoming indispensable tools. They enhance the accuracy, spatial resolution, and overall utility of numerical models by providing high-resolution, real-time data that can be used for assimilation, and validation. One of the limitations of traditional observation methods, such as moored time series, is their restricted spatial coverage and high operational costs. In contrast, the wider deployment of affordable sensors has significantly increased the volume and diversity of observational data available, ultimately improving the reliability and precision of ocean forecasts and reanalysis.

Figure 7: Operational oceanography concept showing how low-cost technologies can contribute to validation and data assimilation processes.



The integration of low-cost sensor technologies also expands the practical applications of operational oceanography *(Aydoğdu et al. 2016; Kerry et al. 2024)*. These include areas such as disaster preparedness, fisheries management, and shipping route optimization. For instance, real-time temperature and salinity data collected by these sensors **support models that forecast hurricane formation and trajectories, enabling faster and more effective emergency responses**. Similarly, measurements of current velocity and water column stratification **inform navigation strategies that reduce fuel consumption and mitigate environmental impacts**.

Moreover, the fusion of low-cost sensor networks with advanced computational tools, such as machine learning algorithms, further elevates the predictive power of numerical models. By uncovering patterns in large datasets, these tools allow researchers and policymakers to generate actionable insights that support more effective and adaptive marine and coastal management strategies.

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5. Challenges and Limitations

The SWOT analysis presented in section ***"4. Benefits and Advantages of Low-Cost Sensors"*** also provides a panoramic overview of challenges and potential threats to be faced during the implementation of low-cost ocean observing systems.

5.1. Calibration and Data Accuracy

Ensuring consistent and accurate data from low-cost sensors remains a significant challenge. Developing standardised calibration protocols and quality control measures is essential to maintain data integrity and reliability. Calibration must account for environmental variability, including temperature fluctuations, salinity changes, and pressure differences, to ensure the accuracy of collected data. Collaborative efforts between manufacturers, academic institutions, and international organisations can lead to the development of universally accepted calibration methods and standards and commonly adopt Best Practices documentation. Furthermore, the deployment of reference-grade instruments alongside low-cost sensors can help validate and improve data reliability over time.
It is necessary to plan, develop, and support intercalibration programmes and long-term data stability checks, by identifying centers *(or institutes)* with the required technological background and appropriate equipment. In this way, verification and intercomparison tests of different instruments and technologies could be carried out, providing a form of ***"technological validation."*** The ultimate goal should in any case be linked to the identification of Essential Ocean Variables *(EOVs)* dedicated to low-cost technologies, in order to define their limits and potential applications.

CMCC experimental turtle tag equipped with pressure and depth sensors, a multispectral sensor, and a triaxial accelerometer to record turtle movements. An innovative feature is the use of the low-cost GLOBALSTAR satellite network for data transmission. The tags are currently used in the MySea project and by the Torre Guaceto Marine Protected Area (MPA). ©Daniele Piazzolla

5.2. Durability and Reliability in Harsh Marine Environments

Marine environments impose harsh metocean conditions. An exercise of life cycle description is proposed in a dedicated standard *(AFNOR standard NF X 10-812, 2013)*, it includes operational conditions at sea as well as transport and storage conditions : hydrostatic pressure, biological fouling, vibrations but also parameters depending on the intended scope of deployment such as cold, damp heat, salt spray, solar radiation, mechanical shock, movement of the platform, thermal shock at immersion, ground continuity and electromagnetic compatibility.

These harsh conditions can degrade sensor performance and shorten their operational lifespan. Advances in materials science, such as the use of corrosion-resistant alloys and ageing proven thermoplastics, antifouling coatings, and robust encapsulation techniques, are critical to improving sensor durability. Additionally, modular designs that allow for easy replacement of damaged components can extend the usability of low-cost sensors.

The readiness level of the low cost sensors should be evaluated as in any engineering process though in a simplified way. A dedicated Technological Readiness Level scheme is proposed by Waldmann et al.,2010. The 9 levels of the engineering practice are limited to four Ocean Science Technology Readiness Levels *(OS-TRL)*: *(i)* Proof-of-concept/development *(TRL 1–3)*; *(ii)* Research prototyping *(TRL 4–6)*; *(iii)* Dissemination of the technology *(either commercial or through other partnership) (TRL 7–8)*; *(iv)* Mission proved *(TRL 9)*. The transition from OS-TRL stage ii to iii should include independent testing, validation and verification. Innovative access to testing facilities or combined qualification sessions must be investigated to cover the cost of this stage. The ***"Transnational Access"*** proposed by several EC funded research infrastructures could be extended for this purpose.

Long-term field trials in diverse marine environments *(OS-TRL iv)* further refine sensor reliability and adaptability, ensuring that they perform effectively across varying conditions.

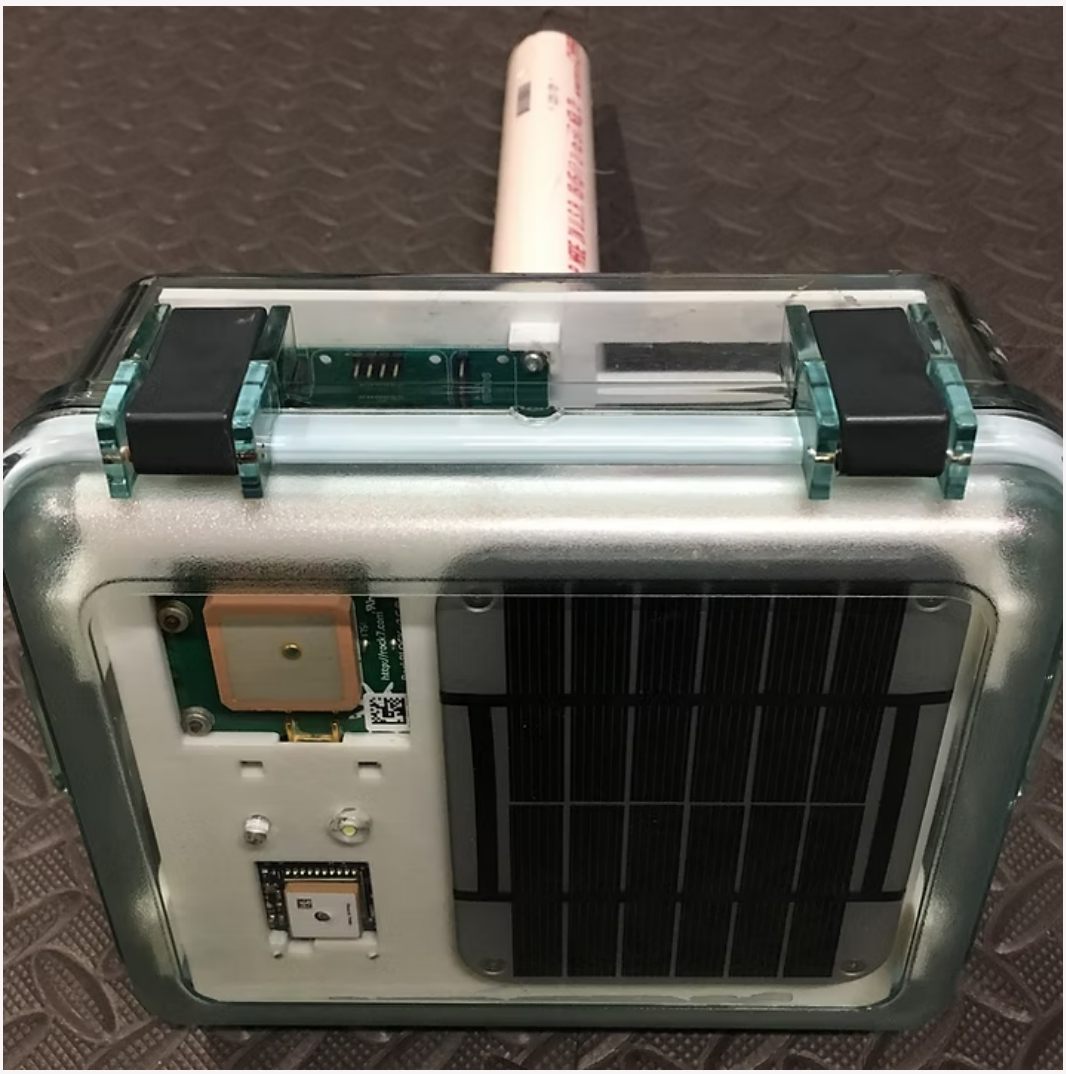
With regard to maintenance aspects, as with all marine instrumentation, this remains a crucial issue. The low cost could represent a disadvantage, since some antifouling solutions, for example, may be expensive; however, it could also be an advantage, as in the medium term it would allow for the replacement of equipment at low expense. Moreover, the low-cost approach itself provides an incentive to address this challenge through the development of innovative and affordable solutions. Finally, the use of automatic data quality assessment systems based on artificial intelligence could ensure more timely interventions *(see Chapters 6 and 7)*.

5.3. Data Transmission and Connectivity

Reliable data transmission and integration into existing systems pose logistical and technological hurdles. Marine observation networks often operate in remote areas with limited connectivity, requiring innovative solutions for data collection and transfer.

Advances in satellite communication technologies, including the use of low-Earth orbit *(LEO)* satellites, have enhanced data transmission capabilities. The integration of Internet of Things *(IoT)* technologies *(de Camargo et al., 2023)* allows sensors to form networks that share data in real time *(Bogdan et al., 2023; Chandrappa et al., 2017)*.

However, challenges remain in ensuring affordability and energy efficiency for long-term deployments. Hybrid solutions, such as combining satellite uplinks with local mesh networks, offer promising avenues for addressing these issues.



Maker Buoy or my LLC ©WRG LLC

5.4. Standardisation and Integration with Existing Systems

The lack of standardisation complicates the integration of low-cost technologies with established observation frameworks. Variations in data formats, sensor specifications, and calibration methods can hinder interoperability and data comparability. Collaborative efforts to develop common standards and protocols are essential for maximizing the utility of these tools. Initiatives such as GOOS are working to create unified frameworks that facilitate seamless data sharing and integration. Establishing certification programmes for low-cost sensors can also ensure compliance with international standards, promoting their adoption within larger monitoring networks. In fact, it is crucial to pay a lot of attention to the integration of existing time series with new data in order to be able to use them in the calibration as well as in the validation and assimilation procedures. Additionally, a rather rapacious dog-eat-dog competition might be established between vendors with proven solutions, leading to a potential market saturation. Besides, changing industry regulations and environmental policies may affect future deployments and data collection. Low-cost manufacturers may not always be able to meet the same certification requirements or legal standard, which limits their appeal for high-stakes applications that demand reliable, certified performance.

Low-cost drifter ©OGS

5.5. Appropriateness: Tailoring for "Fitness-for-Purpose"

The advent of low-cost technologies for observing the marine environment offers unprecedented opportunities to bring affordable ocean science research and related services to resource-constrained countires of the Global South in support of their sustainable development goals. However, the routine implementation of such solutions in similar circumstances will ultimately depend on their ***"appropriateness"***. Appropriateness, both as a concept and approach *(Lissenden et al., 2014)*, is not so much about the specific engineering design of a product but rather its capacity for adaptation to a given context. Ultimately, this boils down to the degree of flexibility that can be built into a low-cost device's scientific data acquisition steps and data handling architecture to allow modification sufficient to guarantee usable marine environmental data reliably in the conditions of effective utilization in a way that meets the requirements and recommendations of the international frameworks governing marine data quality.

The data quality paradigm that is currently gaining ground in the field of marine observation is complex and multidimensional, with a heavy emphasis on ***"fitness-for-purpose"***, a requisite that is sure to impact more and more the implementation of currently mature observing technologies also. The change in focus is towards ***"suitability at point of use"***, which has a number of important implications: *(i)* the quality of data will vary depending on how they will be used; *(ii)* the quality of data will need to be viewed in terms of the characteristics of the results of the underlying measurements; *(iii)* the number of ***"data quality dimensions"*** that must be selected to assess the quality of data should be sufficient to describe their usability with respect to requirements. From the perspective of the application of low-cost technologies to marine observations, this will mean, at the very least, taking steps to:

- Establish common guidelines for standardising relevant measurand definitions and reference materials;
- Establish common guidelines for developing dedicated device calibration procedures and operating practices;
- Explore, and possibly define, practicable approaches to assist in the estimation of data uncertainty; and
- Build a unified platform to help coordinate and promote training in the specific domain.

6. Best Practices for Implementing Low-Cost Sensors

6.1. Calibration and Quality Control Protocols

Establishing rigorous protocols ensures data reliability and accuracy across diverse deployments. An effective calibration strategy includes initial laboratory calibration using traceable standards, followed by in situ cross-validation during deployment. This chain of events includes laboratory routine calibration, field validation, and cross-comparison with high-precision instruments. Calibration must account for environmental variability, such as temperature fluctuations, salinity gradients, and biofouling, which can significantly impact sensor performance or the soil stability that can profoundly affect sea level measurements.

Field validation efforts should incorporate controlled testing environments where sensors are exposed to known conditions, providing benchmarks for performance evaluation. Additionally, integrating advanced technologies, such as automated calibration systems and machine learning algorithms, can streamline quality control processes and minimize human error. Such quality controls should encompass both real-time and delayed-mode checks, similarly to those applied in operational oceanography. The first one is based on automated, robust quality tests for use in real-time; the second one is based on the best available quality controls, often including manual intervention, but available with a longer delay and expected to provide improved accuracy level *(Davidson et al., 2019)*.

Collaborative networks among research institutions, manufacturers, and policymakers can foster the development of universal calibration standards, ensuring that data from low-cost sensors align with international best practices. These efforts are particularly vital for scaling deployments across diverse ecosystems while maintaining consistency and reliability. Moreover, deploying a system of reference instruments in parallel with low-cost sensors during critical data collection periods can provide valuable cross-validation for datasets.

The use of cloud-based platforms to store and analyze calibration data enables real-time monitoring of sensor performance. This continuous feedback mechanism allows for proactive adjustments, extending sensor longevity and enhancing data quality over time.

6.2. Intercalibration and Standardisation Efforts

Collaboration among stakeholders can drive standardisation, facilitating broader adoption and interoperability. Intercalibration initiatives, where multiple sensors are tested simultaneously under identical conditions, provide critical insights into variability across devices and manufacturers. Such efforts enable the identification of discrepancies and the refinement of measurement techniques, ensuring that all sensors perform to a common standard.

Harmonizing data formats and metadata standards is equally important for integrating low-cost sensors into global observation networks. For instance, adhering to protocols established by GOOS or the Argo programme ensures that data collected by low-cost sensors can be seamlessly incorporated into broader datasets, enhancing their scientific utility.

International workshops, technical committees, and shared testing facilities can further support standardisation efforts, fostering collaboration between developed and developing economies. This inclusivity ensures that the benefits of advanced observational frameworks extend to all regions, promoting equitable access to high-quality marine data. Such collaborations could be augmented by regional centers of excellence that provide technical training, access to testing facilities, and the development of region-specific calibration methods.

Furthermore, standardisation efforts can extend to the development of modular sensor components, enabling the creation of interchangeable parts that streamline maintenance and reduce costs. Standardised interfaces for sensor data transfer also ensure compatibility with diverse data management systems, simplifying integration processes.

OpenCTD probe. ©Allie Wilkinson

6.3. Data Management and Sharing

Efficient data management systems promote accessibility, fostering collaboration and advancing scientific discovery. This includes the development of user-friendly platforms for data storage, analysis, and dissemination. Cloud-based systems, such as Google Earth Engine or Copernicus Marine Environment Monitoring Service *(CMEMS)*, provide robust frameworks for handling large datasets while enabling real-time data processing and sharing.

Data sharing protocols should prioritize open access while ensuring data security and proper attribution. Implementing standardised data formats, such as NetCDF *(Network Common Data Form)* or LOD *(Linked Open Data) (Bizer et al., 2018)*, simplifies integration across platforms and facilitates interoperability. Moreover, metadata tagging, which includes detailed contextual information about sensor deployments and environmental conditions, enhances the interpretability and reproducibility of datasets.

Engaging local communities and citizen scientists in data sharing initiatives can further enrich datasets, adding valuable local insights and fostering a sense of ownership among stakeholders. Training workshops, webinars, and user guides can support these efforts, building capacity for effective data management at all levels.

Advanced data visualisation tools, such as interactive dashboards and GIS-based platforms, can democratize access to complex datasets, enabling stakeholders with varying technical expertise to interpret and utilize the information effectively. Leveraging artificial intelligence and machine learning for data analysis can further uncover patterns and trends, optimizing decision-making processes in marine management.

By leveraging these best practices, low-cost sensors can contribute to a more inclusive and dynamic global marine research community. Moreover, fostering international data-sharing agreements and establishing centralized repositories for marine data can accelerate scientific advancements, support policy development, and drive sustainable management of marine resources.

6.4. Long-term Validation

In this context, it is essential to validate low-cost sensors over a sufficiently long period to ensure the absence of significant measurement drift. This process is crucial not only for assessing the sensor's performance but also for guaranteeing the consistency and reliability of the data produced over time.

Even if such sensors may not match the accuracy levels of high-end scientific instruments, their long-term stability must be confirmed to ensure that the quality of the measurements remains constant. Without proper validation, temporal changes in the sensor output could be misinterpreted as environmental variability rather than instrumental deviation, thereby compromising the integrity of the dataset.

7. Future Trends and Innovations

7.1. Emerging Technologies in Marine Sensing

Innovations in sensor design, materials, and energy efficiency promise to redefine marine observations. Emerging technologies such as biosensors, nanotechnology, and advanced materials are enabling the development of highly sensitive and durable devices. For example, biosensors capable of detecting specific biochemical markers are being used to monitor water quality and track the presence of harmful algal blooms. Nanotechnology-based sensors provide unparalleled sensitivity, allowing the detection of trace elements and pollutants with high precision.

Advanced materials, including graphene and other nanocomposites, are enhancing sensor durability by improving resistance to biofouling and corrosion in harsh marine environments. Additionally, innovations in energy harvesting, such as piezoelectric materials and wave energy converters, are extending the operational lifespan of sensors by enabling self-powered systems. These advancements are not only expanding the range of measurable parameters but also improving the reliability and affordability of marine sensing technologies.

7.2. The Role of Artificial Intelligence and Machine Learning

Artificial Intelligence *(AI)* and Machine Learning *(ML)* algorithms are revolutionizing the analysis of marine data by enhancing data processing, pattern recognition, and predictive capabilities. These tools are increasingly being used to analyze large and complex datasets, identify trends, and optimize observation strategies. For instance, AI models are being employed to predict the occurrence of extreme weather events, such as hurricanes, by analyzing historical and real-time oceanographic data.

ML techniques are also enabling automated anomaly detection, such as identifying unusual patterns in ocean temperature or salinity that may indicate ecosystem disruptions. Furthermore, deep learning algorithms are being integrated into image processing systems for species identification and habitat mapping, significantly reducing the time and expertise required for data analysis. By automating repetitive tasks and uncovering hidden patterns, AI and ML are empowering researchers to focus on strategic decision-making and hypothesis generation.

7.3. Advances in Connectivity and Data Transmission

Improved connectivity solutions are enabling seamless data integration and global monitoring networks. Advances in satellite communication, Internet of Things *(IoT)* technology, and 5G networks are facilitating real-time data transmission and analysis. For example, low Earth orbit *(LEO)* satellite constellations, such as Starlink, provide high-speed connectivity in remote marine regions, ensuring that data from distributed sensor networks can be transmitted with minimal latency. In addition to separate satellite services, the 3rd Generation Partnership Project *(3GPP)*[35] introduced support for non-terrestrial networks *(5G-NTN)* in Release 16 *(2020)*, enabling standard cellular modems to attach directly to satellites for truly global coverage [TR 21.916, TS 38.821]. Usage remains limited at present, but operators such as T-Mobile in the United States began offering a Starlink-based NTN service to selected customers in 2025[36]. This capability is expected to expand and could be particularly useful for mobile platforms that wish to conserve power by connecting to terrestrial base stations when in range and seamlessly switching to satellite when out of coverage-all via a single modem.

LoRa Direct to Satellite *(DtS)* is another promising option, where a regular LoRa is used to send data directly to satellites *(Zadorozhny et al., 2022)*. This would offer similar advantages as to the 5G-NTN, but for LoRa-enabled devices.

IoT-enabled marine sensors form interconnected networks that share data in real time, enhancing the spatial and temporal resolution of observations *(Kinar et al., 2022)*. These systems are increasingly integrated with edge computing capabilities, allowing data processing to occur locally, reducing the need for constant connectivity and optimizing bandwidth usage. Furthermore, the integration of 5G technology into coastal observation networks is enabling high-speed, low-latency data transfer, supporting advanced applications such as remote control of autonomous vehicles and real-time video streaming for habitat monitoring.

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35 www.portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3493
portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3525

36 www.t-mobile.com/news/network/t-mobile-starlink-beta-open-for-all-carriers

7.4. Potential for Global Ocean Observing Systems

Affordable technologies play a critical role in building a comprehensive and inclusive global observing network. These systems provide valuable data for addressing global challenges, such as climate change, biodiversity loss, and sustainable development. Initiatives like GOOS and the Argo programme have already demonstrated the feasibility of large-scale, collaborative monitoring efforts. By leveraging low-cost sensors, these programmes can increase the spatial and temporal resolution of data collection, ensuring that critical regions, such as the Global South and remote polar areas, are adequately represented in global datasets.

The incorporation of low-cost technologies also enables real-time monitoring of dynamic oceanographic processes, such as thermohaline circulation, marine heatwaves, and the progression of ocean acidification. These systems allow researchers to identify emerging environmental threats quickly, facilitating timely interventions. For instance, enhanced coverage provided by low-cost sensors has improved the capacity to monitor and predict the impacts of phenomena like El Niño-Southern Oscillation *(ENSO)* events, providing critical information for agricultural and disaster preparedness strategies globally.

Emerging partnerships between governmental organisations, academic institutions, and private entities are driving the development of global observing systems that leverage cost-effective technologies. These collaborations integrate diverse data sources, from satellite observations and autonomous vehicles to Citizen Science contributions, creating a unified framework for addressing complex environmental issues. For example, programmes such as the Blue Planet Initiative and the UN Ocean Decade Data Coordination Platform emphasize the use of affordable technologies to build resilience in underrepresented regions while fostering Ocean Literacy and community engagement.

Citizen science initiatives play a transformative role in these networks by filling observational gaps and empowering local communities. Community-driven monitoring efforts, supported by user-friendly low-cost tools, enable regions with limited scientific infrastructure to participate in global research. These initiatives also enhance local decision-making by providing stakeholders with direct access to relevant and actionable data.

Interoperability remains a key focus for these systems, with efforts directed at harmonizing data formats, calibration standards, and transmission protocols. Global efforts, such as the development of FAIR *(Findable, Accessible, Interoperable, Reusable)* data principles, are streamlining these processes, ensuring that data collected from diverse sources are comparable and accessible. Additionally, artificial intelligence *(AI)* and machine learning *(ML)* integration enhances the utility of global ocean observing systems, enabling the analysis of large and complex datasets to uncover trends, patterns, and anomalies.

By enabling data sharing and fostering interdisciplinary research, global observing systems have the potential to transform our understanding of ocean processes. These systems also play a critical role in meeting international environmental agreements, such as the Paris Agreement and the United Nations Sustainable Development Goals *(SDGs)*. The data and insights generated by these networks inform evidence-based policy decisions, advance sustainable resource management, and support adaptive strategies to mitigate the impacts of climate change.

Through collaborative and inclusive approaches, global ocean observing systems supported by affordable technologies provide a pathway for addressing the pressing environmental challenges of our time. By bridging technological innovation with societal needs, these systems ensure that the benefits of marine science are accessible to all, safeguarding marine ecosystems and their services for future generations.

7.5. Societal Engagement and Ocean Literacy: Applications of Low-Cost Technologies

Ocean Literacy, defined as comprehension of the reciprocal relationship between the ocean's influence on individuals and their impact on the ocean, encouranges public engagement in marine science. It serves as an important link between oceanography and research, policy, society, and industry, enabling awareness and trust in science, and supporting sustained and fit-for-purpose ocean observing systems. Ocean Literacy also provides reserach, oceanographic, environmental, and meteorological agencies with opportunities to engage diverse audiences across generations, professions, and socio-economic groups. This fosters intellectual, emotional, and creative connections with different sectors of society, helping scientific institutions resonate more deeply with the public *(Eparkhina et al, 2021, 2026)*.

Low-cost technologies foster societal engagement by democratising access to marine observation tools and improving Ocean Literacy. By involving local communities in data collection and decision-making processes, these tools contribute to more equitable and effective ocean governance. For example, community-driven programmes using affordable sensors to monitor water quality or track coastal erosion empower stakeholders to take proactive measures in managing their local environments.

These approaches offer significant potential to democratize environmental monitoring by empowering non-experts to participate actively in data collection and analysis *(Merlino et al. 2021, 2023a; Giugliano et al. 2025)*.

Through the deployment of affordable sensors, open-source software, and interactive visualisation tools, such initiatives can substantially broaden spatial and temporal data coverage, thereby contributing to the advancement of oceanographic knowledge and the achievement of global sustainability targets, including those outlined in the United Nations Sustainable Development Goals *(SDGs)*.

Educational initiatives leveraging low-cost technologies are enhancing public awareness of ocean issues, inspiring the next generation of marine scientists and conservationists. Interactive tools, such as app-based platforms and virtual reality simulations, allow users to visualise and interact with marine data, making complex concepts more accessible. Moreover, Citizen Science programmes supported by low-cost sensors are creating opportunities for individuals to contribute meaningful data to scientific research, fostering a sense of ownership and responsibility for marine conservation and ocean observing efforts.

By bridging the gap between scientific research and public engagement, low-cost technologies are driving a cultural shift toward greater stewardship of the ocean. These efforts not only help increase the resilience of coastal communities but also contribute to achieving global sustainability goals by promoting informed and collaborative decision-making. Furthermore, participatory models encourage more inclusive and informed policymaking. To fully realize these benefits, it is essential to address key challenges related to data reliability, standardisation, and scalability. Additionally, advocacy for inclusive education and the development of ethical guidelines must be prioritized to ensure responsible practices and to maximize both community and environmental benefits.

HCMR students discussion with fishermen in Elounda bay. ©HCMR

8. Conclusion

8.1. Summary of Key Findings

Low-cost technologies offer transformative potential for coastal and open ocean oceanographic observations, addressing crucial gaps in spatial and temporal coverage. By enabling broader participation and fostering innovation, these tools have the potential to revolutionize marine science and resource management.

INVEST
Funding the future of ocean observation

POLICY
Frameworks that enable innovation

COLLABORATE
Uniting governments, academia, and communities

OPEN
Science, data, and hardware

EMPOWER
Citizens as scientists, communities as guardians

TRAIN
Building capacity from grassroots to experts

INNOVATE
Low-cost, high-impact technologies

STANDARDIZE
Ensuring quality and interoperability

SUSTAIN
Long-term infrastructure and support

The integration of affordable, scalable technologies into global observation systems **enhances data accessibility and democratizes marine research, fostering collaboration across disciplines and regions**. These advancements are instrumental in addressing urgent global challenges, including climate change, habitat loss, and the sustainable use of marine resources.

Key findings demonstrate that low-cost technologies can enhance observational reach, democratize data access, and foster international collaboration. By empowering local stakeholders and incorporating Citizen Science into marine research, these tools contribute significantly to global environmental monitoring and policy development.

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8.2. Recommendations for Policymakers and Researchers

The advancement of low-cost and cost-effective ocean technologies requires coordinated structural action. Incremental improvements alone are unlikely to meet emerging policy, operational, and climate adaptation demands; systemic transformation is necessary to ensure equitable access to ocean data, long-term resilience of observing systems, and alignment with global sustainability agendas, including EU cohesion objectives, Blue Economy resilience, and the European Ocean Pact Priorities. The following recommendations are intended to guide policymakers, funding agencies, research institutions, and innovation ecosystems toward a coherent and scalable implementation pathway.

- **Invest in Research and Development:** Allocate targeted and sustained funding to enhance sensor accuracy, durability, and scalability, and optimise total cost of ownership *(TCO)*, ensuring reliability and long-term usability across diverse marine environments. Such investments are essential to guarantee data quality standards compatible with global observing frameworks and to build confidence in low-cost technologies as credible components of national and international monitoring systems.
- **Promote Policy Support:** Develop and implement policies that encourage the adoption and deployment of affordable technologies in marine observation networks. Research and innovation funding programmes should explicitly consider and incentivise the use of low-cost instrumentation, including through procurement reform, interoperability standards, and long-term funding mechanisms. Dedicated evaluation criteria should recognise scalability, cost-efficiency, modularity, and open-hardware approaches, and measurable performance benchmarks, while allowing flexible and innovative investment strategies, including distributed acquisition models and alternative procurement pathways. Such regulatory adjustments are fundamental to removing structural barriers that currently favour high-capital solutions and to stimulating innovation across the marine technology sector.
- **Foster Stakeholder Collaboration:** Strengthen and formalise partnerships among governments, research and academic institutions, industry, and coastal communities to facilitate standardisation, interoperability, data sharing, and capacity building. Effective collaboration across local, national, and international levels is essential to ensure alignment with global observing frameworks such as GOOS and UN Ocean Decade, and to prevent fragmentation of data systems. Structured cooperation mechanisms can accelerate innovation uptake, reduce duplication of efforts, and enhance the long-term resilience and coherence of marine observation networks.
- **Encourage Open Science:** Support the development of interoperable, open-access platforms for data dissemination, analysis and long-term stewardship, ensuring that marine data are accessible to all stakeholders, including researchers, policymakers, educators, and the public. Open Science practices should align with international standards and FAIR principles

(Findable, Accessible, Interoperable, Reusable), enhancing transparency, reproducibility, and scientific credibility. Inclusive data ecosystems strengthen evidence-based decision-making, promote public trust, and maximise the societal return on investment in ocean observing systems.

- **Integrate Citizen Science:** Leverage community-driven initiatives to expand spatial and temporal observational coverage while strengthening societal engagement in ocean research and conservation, in line with the UN Ocean Decade's emphasis on co-design and inclusive participation. Establish long-term institutional and financial support for robust data infrastructures capable of storing, archiving, validating, and visualising Citizen Science data. Clear quality-control protocols and integration pathways with professional observing systems are essential to ensure scientific credibility, interoperability, and policy relevance. Citizen Science initiatives should also be explicitly linked to Ocean Literacy strategies, enhancing public understanding of ocean processes, data interpretation and literacy, and the societal relevance of marine observations.
- **Expand Training Programmes:** Develop structured educational and technical training initiatives to equip local communities, technicians, and early-career researchers with the skills required to deploy, calibrate, maintain, and manage low-cost ocean observing technologies. Long-term capacity development is essential to ensure technological self-reliance, reduce maintenance dependency, and strengthen regional resilience, particularly in coastal and developing regions. Dedicated training initiatives should actively involve countries with emerging and developing economies, fostering dissemination of specialised competencies, expanding Citizen Science participation, and promoting technological autonomy. Embedding these programmes within academic curricula and professional training frameworks will support the formation of a new generation of ocean practitioners capable of sustaining scalable and cost-effective observing systems.
- **Promote Open-Source Hardware Ecosystems:** Support the development and adoption of open-source hardware through targeted funding mechanisms, standards development initiatives, and dedicated innovation programmes. Prioritise the co-design of open standards for interfaces, calibration procedures, metadata, and QA/QC workflows, and validation protocols so that open-source solutions remain interoperable, comparable, and fully usable within national and global observing systems. Encourage systematic documentation and open publication of hardware designs to enhance transparency, reproducibility, and collaborative technological advancement. Strengthening local and regional communities of innovators will enhance technological autonomy, foster knowledge exchange, and accelerate context-specific adaptation of marine observing technologies.

8.3. Call to Action for Advancing Low-Cost and Cost-Effective Oceanography

The transition toward low-cost and cost-effective ocean observing technologies is no longer optional; it is a strategic enabler of scalable impact for the future sustainability of global ocean observing systems. As climate change accelerates, coastal pressures intensify, and the demand for actionable ocean data increases, stakeholders must align efforts to scale accessible, resilient, and interoperable observing solutions.

This **call to action** is aimed primarily at the **global scientific community**, policy and **decision makers**, **educational institutions**, and **science communication actors**. Researchers are called upon to validate, refine, and integrate low-cost technologies within established scientific frameworks. Policymakers and public authorities must incorporate these scalable solutions into national and regional monitoring strategies. Educational systems, from universities to technical institutes, should adopt and disseminate low-cost ocean technologies as tools for capacity building and workforce development. Science communicators play a critical role in translating accessible ocean data into societal awareness and public engagement.

Low-cost technologies are not merely budget alternatives; they represent enabling infrastructure for expanding spatial and temporal coverage of ocean observations. By lowering barriers to deployment, these systems democratize access to marine data, reduce dependency on high-capital centralized platforms, and empower emerging economies and coastal communities to actively participate in ocean monitoring. In doing so, they directly contribute to narrowing the global observation gap and strengthening scientific equity.

Strategic collaboration should therefore focus on three priority pillars:

- **Technological Integration and Interoperability:** Ensuring that low-cost sensors and platforms comply with international data standards, remain interoperable within global observing networks, and integrate seamlessly into digital ocean infrastructures, cloud-based platforms, and real-time analytics systems.
- **Scalable Deployment Models:** Promoting modular, replicable architectures deployable across diverse marine environments, from open oceans to continental shelves, ports, lagoons, and remote coastal regions. Scalability must extend beyond hardware to include calibration protocols, quality assurance frameworks, defined validation procedures, measurable performance benchmarks, maintenance logistics, and long-term data stewardship.
- **Sustainable Economic Frameworks:** Advancing cost-effective oceanography requires viable financial and governance models. Public-private partnerships, distributed manufacturing, shared infrastructure networks, and data-as-a-service approaches can significantly reduce total cost of ownership while stimulating innovation and regional Blue Economy development.

The societal implications of this transformation are substantial. Low-cost observing systems enhance early warning capabilities, strengthen climate adaptation strategies, support ecosystem-based management, and reinforce cross-sector and cross-border coordination necessary for effective implementation of environmental and restoration policies. In education, they provide hands-on platforms for training the next generation of ocean scientists and technicians. In communication, they enable transparent, open-data environments that foster trust, inclusivity, and informed public discourse.

Within the framework of the Global Ocean Observing System 2030 Strategy and the EuroGOOS Strategy 2030, innovation in observing technologies and networks is recognized as foundational to building an integrated, responsive, and sustained global and regional observing system. Achieving full implementation of Essential Ocean Variables *(EOVs)* requires extending measurements beyond the open ocean into continental shelf and coastal systems - areas where ecological vulnerability and human exposure are highest. This expansion demands adaptive, distributed, economically sustainable, and interoperable technological solutions, supporting the UN Ocean Decade Challenge 7 Sustainably expand the Global Ocean Observing System.

Over the past decade, GOOS has broadened its scope to include operational services and marine ecosystem health, particularly in coastal regions where much of the global population resides. To meet these evolving objectives, the observing community must adopt a hybrid architecture in which high-end research infrastructures coexist with dense, distributed, and affordable sensing networks.

The call to action is therefore clear: **invest in scalable innovation, institutionalize interoperability standards, foster inclusive scientific and educational capacity building, and embed low-cost technologies within national and international observing strategies.** Only through coordinated and sustained commitment, across science, governance, education, and communication, can we ensure a resilient, equitable, and economically sustainable future for the world's ocean, where scientific excellence and societal progress advance together.

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Annex I – List of EuroGOOS member organisations

Belgium

Agency for Maritime and Coastal Services, Coastal Division *(MDK)*
Royal Belgian Institute of Natural Sciences *(RBINS)*

Croatia
Croatian Meteorological and Hydrological Service *(DHMZ)*
Institute of Oceanography and Fisheries *(IOR)*

Cyprus
The Cyprus Marine and Maritime Institute *(CMMI)*

Denmark

Danish Meteorological Institute *(DMI)*
Defence Centre for Operational Oceanography *(FCOO)*

Estonia

Tallinn University of Technology *(TalTech)*

Finland

Finnish Meteorological Institute *(FMI)*

France

French Naval Hydrographic and Oceanographic Service *(SHOM)*
French Research Institute for Exploitation of the Sea *(Ifremer)*
Mercator Ocean International *(MOi)*
The French National Centre for Scientific Research *(CNRS)*

Germany

Federal Maritime and Hydrographic Agency *(BSH)*
Helmholtz-Zentrum Hereon

Greece

Hellenic Centre for Marine Research *(HCMR)*

Ireland

Irish Meteorological Service *(Met Éireann)*
Marine Institute *(MI)*

Italy

Euro-Mediterranean Center on Climate Change *(CMCC)*
Italian National Agency for New Technologies, Energy and Sustainable Economic Development *(ENEA)*
Italian National Institute for Environmental Protection and Research *(ISPRA)*
National Institute of Geophysics and Volcanology *(INGV)*

National Institute of Oceanography and Experimental Geophysics *(OGS)*
National Research Council of Italy *(CNR)*

Netherlands

Deltares
Rijkswaterstaat – Water, Traffic and Environment
Royal Netherlands Meteorological Institute *(KNMI)*

Norway

Institute of Marine Research *(IMR)*
Nansen Environmental and Remote Sensing Center *(NERSC)*
Norwegian Institute for Water Research *(NIVA)*
Norwegian Meteorological Institute *(MET Norway)*

Poland

Gdynia Maritime University, Maritime Institute
Institute of Meteorology and Water Management *(IMGW-PIB)*
Institute of Oceanology, Polish Academy of Sciences *(IO PAN)*

Portugal

+ATLANTIC CoLAB
Hydrographic Institute *(IH)*
Portuguese Institute for the Ocean and Atmosphere *(IPMA)*

Slovenia

National Institute of Biology *(NIB)*
Slovenian Environment Agency *(ARSO)*

Spain

AZTI
Balearic Islands Coastal Observing and Forecasting System *(SOCIB)*
Oceanic Platform of the Canary Islands *(PLOCAN)*
Puertos del Estado; Spanish Institute of Oceanography *(IEO)*

Sweden

Swedish Meteorological and Hydrological Institute *(SMHI)*

United Kingdom

Centre for Environment, Fisheries and Aquaculture Science *(Cefas)*
National Oceanography Centre *(NOC)*
UK Met Office

Annex II – List of Science Advisory Working Group Members

Co-chairs

Lucie Cocquempot, Ifremer, France
Manfred Zeiler, BSH Marine Science Hub *(BSH)*, Germany

Facilitator

Dina Eparkhina, EuroGOOS, Pan-European

Members

Alejandro Orfila, Mediterranean Institute for Advanced Studies *(IMEDEA)*, Spain
Anna Nikolopoulos, Norwegian Polar Institute *(NPI)*, Norway
Annette Zijderveld, Rijkswaterstaat, Netherlands
Antonio Bonaduce, Nansen Environmental and Remote Sensing Center *(NERSC)*, Norway
Branko Čermelj, National Institute of Biology, Slovenia
Eric Jansen, Euro-Mediterranean Centre on Climate Change *(CMCC)*, Italy
Giovanni Coppini, Euro-Mediterranean Centre on Climate Change *(CMCC)*, Italy
Ghada El Serafy, Deltares, Netherlands
Giuseppe Civitarese, National Institute of Oceanography and Experimental Geophysics *(OGS)*, Italy
Helene Frigstad, Norwegian Institute for Water Research *(NIVA)*, Norway
Henning Wehde, Institute of Marine Research *(IMR)*, Norway
Holger Brix, Helmholtz-Zentrum Geesthacht *(HZG)*, Germany
Joanna Staneva, Helmholtz-Zentrum Geesthacht *(HZG)*, Germany
Julien Mader, AZTI, Spain
Jun She, Danish Meteorological Institute *(DMI)*, Denmark
Laura Tuomi, Finnish Meteorological Institute *(FMI)*, Finland
Luísa Lamas, Hidrográfico Portugal, Portugal
Manuel Ruiz Villareal, Spanish Institute of Oceanography *(IEO)*, Spain
Marco Marcelli, Euro-Mediterranean Centre on Climate Change *(CMCC)*, Italy
Sara Morucci, Italian Institute for Environmental Protection and Research *(ISPRA)*, Italy
Sebastien Legrand, Royal Belgian Institute of Natural Sciences *(RBINS)*, Belgium
Simona Simoncelli, National Institute of Geophysics and Volcanology *(INGV)*, Italy
Vidar Lien, Institute of Marine Research *(IMR)*, Norway

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