EuroGOOS
European Global Ocean Observing System

EuroGOOS Annual General Assembly Meeting
19-21 May 2025
Helsinki, Finland

Agenda Item 2: Open Session on EuroGOOS Activities

Document 2.9: Low-Cost Technologies White Paper Draft

Technological development for sustainable low-cost marine observations

Index of contents

1. Introduction

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

To sustain ocean-based economic activities, advancing knowledge and forecasting within the framework of climate research (WMO), the 2021–2030 UN Ocean Decade, and the G7 Future of the Seas and Oceans Initiative have been identified as absolute priorities. Central to these efforts is the development of a sustained, multi-disciplinary, integrated ocean observing system.

Integrated ocean observing systems are designed to provide critical information to scientists, stakeholders, and end-users - for example, by feeding information into models to improve forecasts.

However, their long-term sustainability depends on the development of low-cost technologies to enhance observing capabilities (Marcelli et al., 2021), including improved spatial and temporal resolution, while reducing observation costs and addressing observational gaps, especially in ocean biogeochemistry and biology (Wang et al., 2019). This approach aims to achieve 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 2021-2030 Vision (Miloslavich et al., 2024)

Within the UN OceanDecade, The CoastPredict Program (https://www.coastpredict.org), a programme endorsed by the UN Decade of Ocean Science and one of the three co-designed with GOOS (The Global Ocean Observing System), 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, it will be a key component of GlobalCoast, the CoastPredict's Framework for Implementation (https://www.coastpredict.org/globalcoast/).

The European community has been very active in promoting cost effective as well as low-cost solutions, "la French Low Tech" (the terminology has not yet been fixed) whether through numerous European projects (LandSeaLot, CS-MACH1, NAUTILOS, etc.) or reference articles (Butler and Pagniello, 2021; Možek et al., 2024; Pieri et al., 2021). EuroGOOS is a European association of members of the operational oceanography and observation community, organized into various tasks and groups. In March 2024, the Technology Plan Working Group of EuroGOOS helped organize an event at Oceanology International entitled "*Catching the momentum in ocean observing technology: optimizing value and data provision"* which was very well received by the community and brought together various players with a strong interest in low-cost technologies.
In September 2024, the EuroGOOS Scientific Advisory Working Group decided to organize a webinar on the subject of low-cost technologies.

Following the success of this initiative, the idea of producing a white paper was born. The ambition of the paper is to promote low-cost technologies for the implementation of sustainable coastal observing systems. According to the GOOS 2030 Strategy, focal points of the white paper focuses are:

1. low-cost sensors: it is essential to integrate the existing observing systems as wide as possible with new physical, biogeochemical and biological low-cost sensors to improve and extend coastal ocean monitoring capabilities in both spatial and temporal scales and to do this, their cost is currently a significant limit;

2. reliability of low-cost sensors: it is necessary to develop low-cost sensors with the required level of precision and reliability, ensuring that they can be integrated into consolidated observing systems with high quality and potentially utilized in citizen science initiatives;

3. Best practices and quality control: this involves laboratory calibration of new low-cost technologies, including intercalibration features and performance validation or assessment in the field. When possible, these assessments should include intercomparison with existing, well-established technologies. It also includes the development of calibration and validation best practices, as well as standards and minimum requirements tailored to specific applications and aligned with existing global frameworks. These standards should address the temporal and spatial scales of application and ensure robust data quality control;

4. low-cost data transmission systems: the cost of data transmission poses a limitation to the expansion of long-term observation systems, as well as IoT and open cloud access. The proliferation of LoRaWAN networks and the availability of diverse satellite solutions present potential opportunities to overcome this challenge;

5. cost-effective Observing Platforms: Enhancing observational capabilities across diverse spatial and temporal scales is crucial, particularly for coastal systems. This can be achieved by developing and deploying dedicated autonomous platforms designed to optimize coastal observing systems;

6. machine learning techniques applied to data quality assessment and to support operational oceanography;

7. Low tech and open source technologies.

1.1. Purpose and Scope

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

Traditional observation systems, though advanced, are often constrained by high operational costs, limited accessibility, and regional disparities in coverage. By addressing these gaps, the document emphasizes the pivotal role of affordable technologies in democratizing data collection, enabling broader participation in marine science, and enhancing our capacity to address global challenges like climate change, biodiversity loss, and marine resource management.

The scope of this white paper spans technological innovation, practical implementation, and interdisciplinary collaboration, serving as a resource for researchers, policymakers, and educators. It advocates for a paradigm shift toward inclusive, scalable, and cost-effective marine observation strategies that align with global sustainability goals.

Finally, this paper aims to contribute to the establishment of a dedicated team focused on the GOOS (Global Ocean Observing System) Essential Ocean Variables (EOVs) (www.goosocean.org/eov) for coastal observing systems—an issue critical to advancing our understanding and management of coastal environments, which requires precise and standardized monitoring frameworks. The proposed team would prioritize identifying and refining EOVs most relevant to coastal processes, ensuring they address the unique physical, chemical, and biological challenges of nearshore environments. Additionally, the team would be tasked with developing a detailed proposal to define a subset of EOVs specifically tailored for low-cost coastal sea monitoring technologies, including citizen science initiatives, thereby enabling broader and more equitable participation in global monitoring efforts. By leveraging advancements in affordable sensors, automated platforms, and data integration, this initiative would strengthen the capacity for robust, high-resolution coastal monitoring, providing essential data to support ecosystem management, disaster risk reduction, and sustainable development goals.

1.2. Enhancing Coastal Ocean Observations: Key Needs and Requirements

Coastal regions are at the frontline of environmental and socio-economic dynamics. These areas host diverse habitats such as coral reefs, mangroves, and salt marshes, which are crucial for biodiversity and provide natural barriers 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 dynamic environments due to limited spatial and temporal resolution. Current systems are constrained by high costs, technological barriers, and an over-reliance on traditional tools, which are often inaccessible to underfunded regions.

The key requirements for enhancing coastal observations include:

• Development of scalable, low-cost technologies to fill data gaps in under-monitored regions. For instance, deploying low-cost unmanned surface vehicles (USVs) equipped with modular sensors can monitor critical parameters like 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 experience dynamic interactions between terrestrial and marine environments, necessitating collaborative efforts among oceanographers, geologists, ecologists, and social scientists to design comprehensive monitoring frameworks.

• Collaboration between local communities, governments, and international organizations to foster capacity building and knowledge sharing. Engaging local communities ensures that observation networks align with regional socio-economic priorities and promotes ownership of data-driven environmental management strategies.

• Citizen Science plays a pivotal role in coastal marine observing by engaging local communities in data collection, observation, and analysis, thereby enhancing the spatial and temporal coverage of monitoring efforts at low cost. This participatory approach not only fosters public awareness and stewardship of coastal environments but also supplements scientific data with valuable on-the-ground insights. Closely linked to Citizen Science, Community Science emphasizes collective, localized efforts to address specific environmental challenges, promoting co-creation of knowledge between scientists and community members. Together, these approaches democratize science, empower communities, and strengthen the integration of local knowledge with scientific research for effective coastal management and conservation.

Enhanced coastal observation networks have transformative potential for addressing global challenges (Crise et al., 2018), such as adapting to sea-level rise, conserving biodiversity, and managing sustainable fisheries. By improving disaster preparedness through real-time monitoring and predictive modeling, these networks can significantly reduce the socio-economic impacts of extreme events like hurricanes, floods, and tsunamis (Ahmed et al., 2023).

1.3. The Need for Marine Low-Cost Technologies

Traditional oceanographic tools, while sophisticated, are financially and logistically prohibitive for widespread deployment, particularly in developing nations and remote regions. These limitations result in significant data gaps, hindering the ability to address pressing environmental challenges effectively. Low-cost technologies offer a transformative solution by reducing operational barriers, enabling distributed observation networks, and bridging critical gaps in global marine monitoring.

The necessity for low-cost technologies in ocean observing systems is driven by the urgent need to expand global ocean monitoring 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, widespread data collection.
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 miniaturized, 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 storage further facilitates remote access and large-scale data sharing, supporting climate research, marine biodiversity conservation, and disaster preparedness. By democratizing ocean observations, low-cost technologies pave the way for more inclusive (Butler et al. 2021) and collaborative marine science, addressing 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, fishermen and their fishing vessels are the ideal partners for data collection in shelf and coastal seas: sensors attached to the gear can collect water column profiles during normal fishing operations (Van Vranken et al., 2023). This approach allows for cost-effective and scalable data collection which is expanding throughout the world (e.g. Penna et al., 2023; Jakoboski et al. 2024; Hirose et al., 2024; Lago et al., 2025). In fact, thanks to its potential in filling data gaps in marine observation at scale and complementing other GOOS networks, the Fishing Vessel Ocean Observing Network (FVON) has recently been endorsed as a UN Ocean Decade project and has been recognized as an emerging GOOS network[1].

For example, 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 that supports adaptive decision-making in areas heavily impacted by environmental changes. Recent H2020 projects such as NAUTILOS (New approach to underwater technologies for innovative, low-cost ocean observation)[2] have supported the development of cost-effective sensors suitable for this type of applications capable of recording additional EOVs (e.g. dissolved oxygen and chlorophyll; Martinelli et al., 2023; 2024).

Moreover, the 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 observational capacities. For instance, a modular sensor system could begin with basic parameters like temperature and salinity and later integrate more advanced capabilities, such as dissolved oxygen and chlorophyll fluorescence monitoring. This adaptability ensures that even resource-limited regions can benefit from high-quality observational data without the need for prohibitively expensive infrastructure (Batubara et al., 2024). The affordability and ease of deployment of low-cost technologies also make them ideal for citizen science initiatives, where community members actively participate in data collection efforts (Bresnahan et al., 2022). This democratization of marine science fosters inclusivity and ensures that the perspectives and needs of local communities are considered in broader environmental strategies. In turn, these initiatives build a sense of ownership and responsibility among participants, encouraging sustainable practices and greater public engagement with marine conservation efforts (Butler et al., 2021). Furthermore, low-cost technologies enhance collaboration at an international level by enabling data sharing and integration into global observation networks. For example, data collected from low-cost sensors can be incorporated into platforms such as the Global Ocean Observing System (GOOS) or the Argo program, contributing to a more

[1] **https://fvon.org/about-us/**
[2] **https://nautilos-h2020.eu/**

comprehensive understanding of ocean dynamics. Low-cost sea level sensors for storm surges and tsunamis have been widely implemented in recent years across many regions, and they are now contributing in real time to the Global Sea Level Observing System (GLOSS). By democratizing access to marine observations, these technologies reduce disparities between developed and developing nations, ensuring that all regions can contribute to and benefit from collective knowledge and global conservation initiatives (Mariani et al., 2021).

The development of low-cost technologies will also allow for the necessary redundancy of sensors, and therefore of measurements, a fundamental aspect for the development and operation of observing systems capable of meeting the requirements of different spatial and temporal scales, early warning systems, and operational models.

In summary, low-cost marine technologies are not merely a cost-saving measure but a transformative tool for promoting equity, inclusivity, and collaboration in oceanographic research and resource management. By addressing economic and logistical barriers, these technologies provide an essential pathway toward sustainable and effective marine governance at both local and global scales.

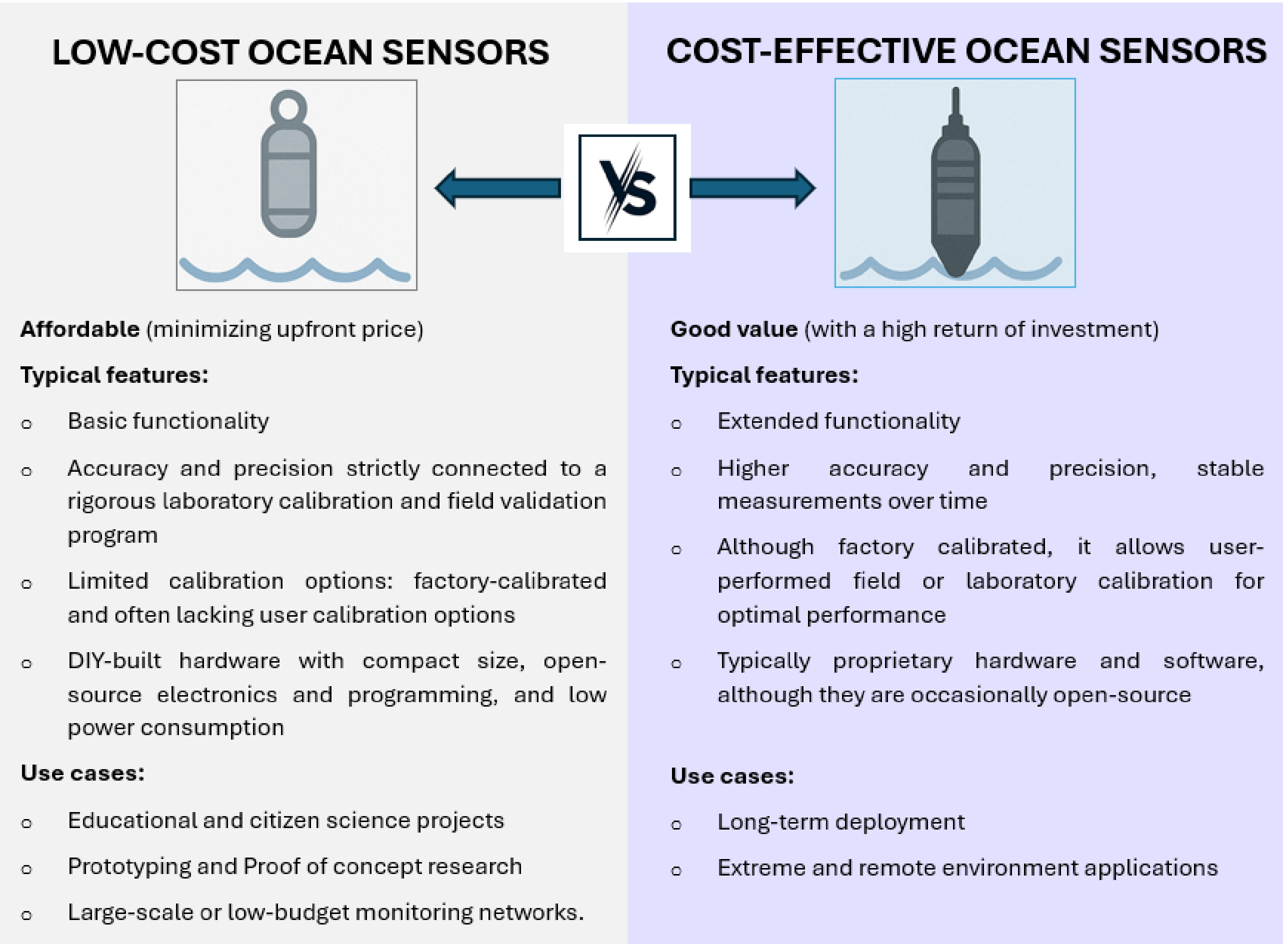

Figure 1. *Basic summary of the main differences between low-cost and cost-effective ocean measurement technologies*

While the terms "low-cost" and "cost-effective" are sometimes used interchangeably, they actually imply different things, especially in the context of ocean sensors, and therefore the subtle distinction should be clearly described herein.

Low-Cost Sensors: Characteristics, Limitations, and Applications

Low-cost sensors are designed to offer affordable and accessible alternatives to traditional 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, which enhances their flexibility for prototyping and educational uses.

A key trade-off for 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 come factory-calibrated and often do not allow for user calibration, limiting their adaptability across different environmental conditions. Therefore, when these sensors are intended for scientific research or environmental monitoring, a comprehensive program of laboratory calibration and in-field validation is essential to ensure data reliability.

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

Despite these limitations, 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. Additionally, they are 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-resolution spatial coverage is prioritized over individual sensor performance.

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

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

In the context of professional, industrial, and research applications—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 provide optimal long-term value through a favorable balance between performance and total cost of ownership (TCO).

Unlike low-cost sensors, which may suffice for short-term or low-risk monitoring, cost-effective sensors are characterized by their capacity to deliver high levels of accuracy, precision, and data stability over extended periods. This performance reliability is essential in applications where consistent and trustworthy data is crucial. Although these sensors may involve a higher initial investment, they typically result in lower operational costs over time due to their durability, reduced maintenance needs, and long 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 functionality. These sensors are often energy-efficient, making them suitable for continuous deployment in remote or autonomous systems.

Additionally, they are designed to produce digital or analog outputs that are readily 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 analytical applications.

As the demand for accurate, stable, and sustainable environmental data increases, the oceanographic community is progressively favoring cost-effective sensor technologies over merely inexpensive alternatives.

Their ability to combine robust performance with economic viability over time positions them as a strategic investment in high-quality, long-term monitoring efforts.

1.4. 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 technologies. This includes detailed analyses of advancements in sensor design, data transmission, and integration with existing systems. Emphasis is placed on how these innovations address the specific challenges of coastal observations. Furthermore, a strengths–weaknesses–opportunities–threats (SWOT) analysis for sustainable low-cost ocean sensors has been performed (Figure 1) as a situational framework to assess the current status, benefits (as later exposed in section 4) and future prospects of deploying such technologies for environmental monitoring and oceanographic research. The SWOT analysis is also useful to detect those challenges and limitations (further analyzed in section 5) associated with this implementation process, eventually helping to foster long-term strategic planning and wise decision-making.

• Advocate for policy frameworks that incentivize 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 and infrastructure development and 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 freely accessible to diverse stakeholders, including academic researchers, policymakers, and community leaders. Such accessibility fosters interdisciplinary collaboration and large-scale analyses that are critical for addressing global environmental issues.

• Provide actionable recommendations for integrating low-cost technologies into global and regional marine observation networks. These recommendations include best practices for sensor deployment in challenging environments, capacity-building programs for local stakeholders, and guidelines for standardizing data formats to ensure interoperability across global networks.

• Improving 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.

The 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 doing so, it aligns with global sustainability goals and international environmental commitments, such as the United Nations Sustainable Development Goals (SDGs).

2. Technological Landscape/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.

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 programs 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 modeling ocean circulation, analyzing long-term variations, predicting climate phenomena, and monitoring marine biodiversity.

Key methodologies in this field 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 program, which provides high-resolution data on sea surface temperature and ocean color, 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 to deploy long term monitoring platforms (see moorings, seafloor and water column fixed point observatories). They used to be unique for the training of ocean observation teams. Real time connections are opening the way to remote interventions of 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 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.

• Research Vessels can be a platform for using or deploying low-cost or low-tech sensors. During transits or operations, there is the opportunity of testing and deploying sensors, other than those used in the planned cruise. This is especially relevant in offshore waters, where the cost of deploying a sensor is conditioned by the access to those areas. Taking advantage of cruises in RV or transits, the cost of deploying sensors in offshore waters can be reduced.

• Fixed point observing systems: Fixed point or eulerian observatories are stationary with respect to their position on or above the seafloor. These fixed platforms host different types of sensors for making a large range of measurements at the surface, on the seabed or throughout the water column. Regardless of 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. This category of observing systems 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).

-Sub- surface 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 to measure 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 have also sub-surface mooring 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 by 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 noticed that both are including more and more coastal sites in their large multi-sites infrastructures.

• 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. 2023a).

• 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 open 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 program 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.

• GLOSS: Tide gauges are 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. 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).

• High Frequency Radars (HFR hereinafter): this consolidated land-based remote sensing technology is based on measurements of the radiowave-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, along with reliable directional wave and wind information, 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:

- 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). Complementary, 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);
- ASV: Autonomous Surface Vehicles are 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. Developing nations, 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.

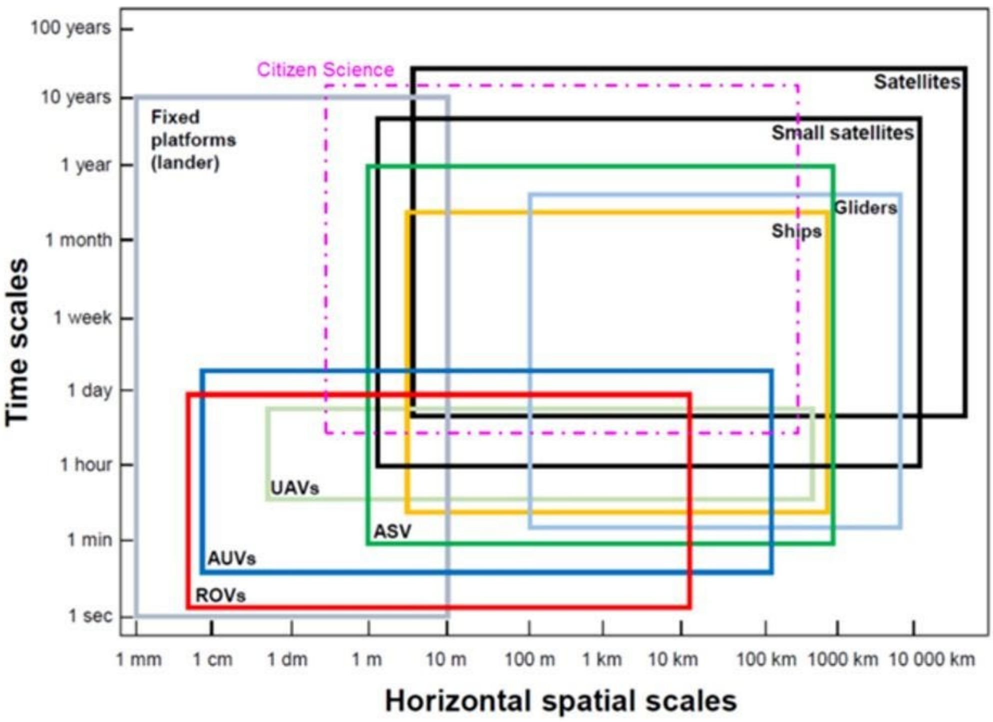

Figure 2. *The image shows the spatial (horizontal) and temporal scales of various measurement platforms, highlighting the distinction between cost-effective and low-cost options (Modified by Nornes, 2018). The lower end of the axis represents resolution, while the upper end represents maximum coverage. [ROV=Remotely Operated Vehicle, ASV=Autonomous Surface Vehicle, UAV=Unmanned Aerial Vehicle AUV=Autonomous Underwater Vehicle). The Cost-Effective platforms are: ROV, ASV, Glider, Argo, AUV, Coastal ship of opportunity (Fishing boat, Coastal Guard, etc.; the Low-Cost platforms are: Mooring of opportunity, Citizen Science, UAV, Specific developments (i.e. OpenMods) Low-cost drifters.*

• 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 to 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 democratizing 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 nations, leaving substantial data gaps in under-monitored regions, particularly 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 democratized 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; Merlino et al. 2023). 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.

2.2. The Need for Low-Cost 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 nations, and enhance data coverage, ultimately advancing both scientific understanding and marine conservation efforts.

2.3. Advancements in Low-Cost Sensors and Technologies

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, 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 program, 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 low-power.

At the same time, integrated circuits originally designed for medical and industrial applications now provide cost-effective solutions for signal conditioning and analog-to-digital conversion, achieving precision levels that were previously unattainable at low cost. The rapid development of miniaturized 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.

b.1.) 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 and technological accessibility.
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, reachable 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 website https://github.com/jack-butler/open-ocean?tab=readme-ov-file, which features open technologies, and on the site https://scoop-ocean.org/ (Solutions for Cost-effective Ocean Observation Platform), where a catalog of low-cost sensors and other cost-effective technologies for ocean study is available.

b.1.1. 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 microcontrollers generation.
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.

b.1.2. 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 measure to calculate salinity. However, they require high-quality circuits and effective anti-fouling strategies to ensure long-term deployment stability mainly for conductivity cell.
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, on 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.
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:
the 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 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.

b.1.3. 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 device was developed during EU MFSTEP project: The T-FLAP (Temperature and Fluorescence Launchable Probe) was an expendable probe (Marcelli et al. 2007) that was tested comparing the results with SBE rosette equipped with 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).
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 for environmental monitoring (Matos et al. 2019) and for Fisheries & Aquaculture. To monitor increased turbidity in the coastal marine environment is fundamental both for seawater quality assessment and because aquaculture can reduce fish production. To address these, 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, 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 (Piermattei et al. 2019).
Advancements in miniaturized 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.

b.1.4. 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, miniaturized, 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 (https://www.dfrobot.com/) and Atlas Scientific (https://www.atlas-scientific.com/) have introduced a range of affordable DO sensors with different specifications to meet different monitoring needs. 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 (Camargo, 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, 2024).

b.1.5. 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 standardization and harmonization of in situ nutrient measurements (Daniel et al., 2019; Petersen et al., 2022). 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., 2023). Although affordable, low-cost nutrient sensors are not yet commercially widespread, recent advancements in miniaturized optical and electrochemical technologies are showing promise. Several prototypes are currently under development, aiming to improve accessibility for long-term ocean monitoring programs (Zhu et al., 2024).

b.1.6. pH and pCO2

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, miniaturized 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 fiber 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 CO2 (pCO2), 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.

b.1.7. 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 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).
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 democratization 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)

b.1.8. 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 micro-plankton communities. The PlanktoScope can be controlled from any WiFi-enabled device, and its versatility allows for rapid reconfiguration to match the evolving needs of the user including citizen scientists.

b.1.9. Sea level, waves and currents

Sea Level

Tide gauges: Low-cost acoustic tide gauges are innovative instruments designed to measure tidal changes in coastal environments at a fraction of the cost of traditional float tide gauges (Frank-Comas et al., 2021). These devices use acoustic signals to determine water levels (including tsunamis, see Zacharia et al., 2011) by measuring the time it takes for sound waves to travel from a transmitter to a receiver, reflecting off the water's surface. Ultrasonic sensors provide multiple benefits, including precise measurements, 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. In addition, tracking atmospheric pressure, air temperature, and humidity is crucial for gaining deeper insights into the mechanisms behind water level fluctuations, storm surge behavior, and compound flooding events. In a harbor environment, these sensors are especially valuable for monitoring water levels in areas with high traffic and varying tidal conditions, which is essential for wise harbor management, safe vessel navigation, and ensuring efficient docking operations (Pérez-Gómez et al., 2022). Their minimal maintenance requirements and ability to withstand harsh marine conditions further enhance their appeal.
CMCC has developed a very low-cost ultrasonic sensor integrated with sensors 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. (https://map.emodnet-physics.eu/platformpage/?platformcode=TG_RIM_01&source=cp&integrator=CMCC).

Waves

In recent years, there has been growing interest in the creation of compact, affordable, and lightweight buoys designed to measure waves at the ocean surface (Collins et al. 2024). The advancement of the Scripps wave drifter as a fixed wave buoy offers significant improvements. Designed originally for free-drifting applications, the Scripps wave drifter (Directional Wave Spectra Drifter-DWSD), can now be anchored to function similarly to a traditional buoy, but with enhanced sensitivity to wave motion and the ability to capture high-frequency wave data. Its modular design and adaptability also make it easier and more cost-effective to deploy in a variety of marine environments, thus expanding the scope and resolution of ocean wave monitoring. It uses GPS-based wave measurement, which offers several advantages, such as the absence of mechanical moving parts that 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 by Lowell Instruments (https://lowellinstruments.com/products/tcm-1-tilt-current-meter/) and the Marotte HS developed by the Marine Geophysics Laboratory at James Cook University (http://www.marinegeophysics.com.au/current-meter). 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. 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). 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.

b.1.10. 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 Global Ocean Observing System (GOOS) that has been endorsed by UNESCO through the UN Ocean Decade as a Decade Project 2021–2030 (McMahon et al., 2021). It provides freely available oceanographic data collected through bio-logging, deploying sensors on marine animals in order to better monitor our changing oceans through the eyes of 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).

Examples

A complementary example at local scale is the Oasis Program (see the link: https://www.socib.es/ca/actualitat/ocean-currents-and-turtles-the-oasis-program-for-marine-conservation), 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.

The SNO MEMO (Service National d’Observation – Microorganismes et Écologie Marine Organisée; see the link: https://sextant.ifremer.fr/geonetwork/srv/api/records/8c8c52b3-4b00-4d11-9dad-37edf6395d82) 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 program emphasizes modularity and standardization 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.

b.1.11. eDNA

Environmental DNA (eDNA) has the potential to transform biodiversity monitoring, but in addition to standardized 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.

b.2.) 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 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 standardized data collection protocols, thereby enhancing spatial and temporal coverage of environmental datasets.

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 has democratized 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.

One notable pilot initiative in this domain is the Fishery Ocean Observing System, which demonstrated the feasibility of integrating artisanal fishers into a broader observational network (Falco et al., 2007). 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. Similarly, sailing vessels have been employed in the Saildrone and other programs to gather oceanographic data across broad transects, demonstrating the viability of long-term, low-cost monitoring (Brewin et al., 2017).

Technological miniaturization 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. Furthermore, the incorporation of smartphone-based tools has revolutionized environmental sensing. For instance, the SmartFluo device, developed under the European FP7 project CITCLOPS, utilizes smartphone components to measure chlorophyll fluorescence, enabling users to assess phytoplankton concentrations at minimal cost (Friedrichs et al., 2017).

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 Program for monitoring jellyfish outbreaks (Boero et al., 2009), the Reef Check initiative for coral reef health assessments (Hodgson, 2001), and the Sea Search Koss program 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).

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, IOT components) make it possible to increase the number of dispersion experiments that can be carried out, and the number of data collected (Merlino et al. 2023a).

Despite their promise, citizen science initiatives require robust data validation frameworks to ensure scientific reliability. Future projects could explore the following areas Machine Learning for Data Validation, Cross-sectoral Integration(e.g., Copernicus Marine Service) to optimize data utility; Capacity Building in the Global South (Developing targeted training and technology transfer programs for coastal communities in the tropics and subtropics); Development of Open-source Sensor Platforms: Promote DIY oceanography kits that allow volunteers to build, calibrate, and deploy their own sensors.

b.3.) Cost-effective approach

b.3.1.) Observing platforms (Michael Oellermann)

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, Ref 1) to €124 million for mid-sized global vessels (Sonne II, Ref 1) and up to €1.185 billion for icebreaking ships like Polarstern II (Ref 1). 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 (www.liquid-robotics.com/) 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).

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 democratizing 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 (MakerBuoy, Butler and 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.

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 programs 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. Additionally, private and professional sailing boats have begun contributing real-time ocean and atmospheric data such as during global yacht races (e.g. Vendeé Globe, The Ocean Race), as part of dedicated Citizen Science Programs (Sailing4Oxygen, SeaKeepers, Sailing4Science, Apparent Winds), or purpose built private expedition sailboats (e.g. Tara, Dagmar Aaen, S/Y Eugen Seibold, Pachamama) collecting even emerging parameters like eDNA (Citizens of the Sea). 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 program (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). Ocean Decade Corporate Data Group includes Fugro with Alcatel Submarine Networks, Ava Ocean, CGG, Equinor and Ørsted. Their determination to creating 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).

b.3.2.) 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 standardized 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.

b.4.) 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. 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 [1]. 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 democratizing 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.

b.5) 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. 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.

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 is 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).

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 (GEO, https://www.inmarsat.com), Iridium (LEO, https://www.iridium.com), Eutelsat (GEO, https://www.eutelsat.com/), Globalstar (LEO, https://www.globalstar.com/en-us/products/iot) , and Thuraya (GEO, https://thuraya.com) (Centenaro et al., 2021).

2.3. Key Challenges in Marine Observations

One of the key challenges in marine observations lies in achieving comprehensive spatial and temporal coverage of the vast and dynamic oceanic environment. The high cost and logistical complexity of deploying and maintaining observation 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 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 innovations 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, integrating heterogeneous data sources (e.g., satellite remote sensing, in-situ measurements, and numerical models) continues to pose technical challenges related to data standardization, quality control, and interoperability. Climate change adds further urgency and complexity, as it intensifies the need for long-term, high-resolution datasets to monitor rapid environmental changes and their impacts on marine ecosystems. Addressing these challenges requires international collaboration, sustained investment, technological innovation, and the continued development of robust, scalable, and affordable global ocean observing systems.

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., 2012). 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., 2023l; 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. 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 programs. In these initiatives, local stakeholders are trained to deploy and maintain sensors, empowering them to participate in data collection and management actively. These programs not only enhance observational coverage but also promote ocean literacy and a sense of stewardship among coastal populations.

In summary, 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) program and the Ship of Opportunity Program (SOOP) are critical components of the Global Ocean Observing System (GOOS), contributing to long-term, large-scale oceanographic and meteorological data collection. The VOS program, 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 programs 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).

3.3 Deep sea applications

Deep seas (under 200 m water depth) are including 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 Ocean Decade objectives are opening the minds for a 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 (MedGOOS) others to shallow water (NOOS).

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 pollutions 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 (ref 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 2 000 mwd.

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 (EOOS, 2024) 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 (ref 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 standardized 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 (sea level, ocean temperature, etc.), 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 standardized 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 various EU's Integrated Maritime Policy, supporting initiatives such as the Marine Strategy Framework Directive, Blue Growth, and Maritime Spatial Planning, European Member States are required to improve marine monitoring and design monitoring networks.
However, the traditional methods could have low spatial and temporal resolution and could be very expensive. This can be avoided by developing and testing innovative and cost-effective monitoring systems (Danovaro, 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 the Common Fisheries Policy (EU REGULATION 1380/2013) 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; Russo et al. 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 the 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/pCO_2 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 noteworthy 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 integrated 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 programs 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.

In summary, affordable marine observation technologies are indispensable for advancing our understanding of climate change and its impacts on ocean health. By democratizing 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.

4. Benefits and Advantages of Low-Cost Sensors

A SWOT analysis (Figure 1) 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 standardization.

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 organizations 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.

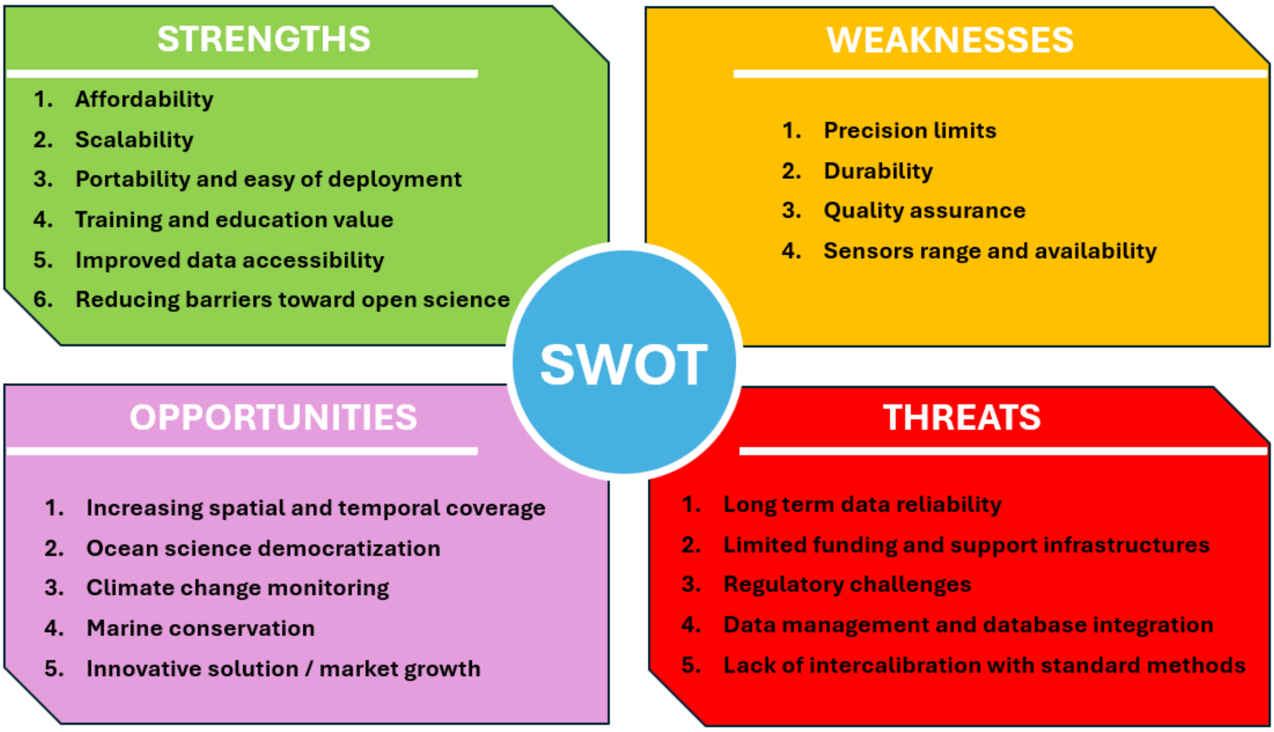

Figure 3. *SWOT analysis of sustainable low-cost ocean sensors.*

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 standardized 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

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 programs, equipped with user-friendly devices, allow local stakeholders to contribute to scientific datasets while gaining a deeper understanding of their marine environments. This democratization of science fosters a sense of ownership and stewardship among participants, encouraging sustainable practices and conservation efforts.

Examples of successful citizen science initiatives include projects where recreational divers use low-cost cameras and sensors to document coral reef health, or where coastal residents measure water quality parameters to track pollution sources. 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, these "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.)

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).

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) organizations.

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.

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.

5. Challenges and Limitations

The SWOT analysis (Figure 1) presented in Section 4 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 standardized 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 organizations 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.

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 Sciences" 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.

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 (Merlino et al. 2023b).

5.4. Standardization and Integration with Existing Systems

The lack of standardization 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 the Global Ocean Observing System (GOOS) are working to create unified frameworks that facilitate seamless data sharing and integration. Establishing certification programs 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.

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 poor and developing nations 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, as a concept (Lissenden et al., 2014), is not so much about the specific engineering design of a product but rather it's 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: (1) the quality of data will vary depending on how they will be used; (2) the quality of data will need to be viewed in terms of the characteristics of the results of the underlying measurements; (3) 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 dedicated common guidelines for standardizing measurand definitions and reference materials;
- establish dedicated common guidelines for developing device calibration procedures and operating practices;
- explore, and possibly define, practicable approaches to assist in the estimation of data uncertainty;
- 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 Standardization Efforts

Collaboration among stakeholders can drive standardization, 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 the Global Ocean Observing System (GOOS) or the Argo program 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 standardization efforts, fostering collaboration between developed and developing nations. 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, standardization efforts can extend to the development of modular sensor components, enabling the creation of interchangeable parts that streamline maintenance and reduce costs. Standardized interfaces for sensor data transfer also ensure compatibility with diverse data management systems, simplifying integration processes.

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 standardized 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 visualization 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 (e.g., IoT, Satellite Communication)

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) 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 Q1 2025 (https://www.t-mobile.com/news/network/t-mobile-starlink-beta-open-for-all-carriers). 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, Merlino et al. 2023b). 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.

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 the Global Ocean Observing System (GOOS) and the Argo program have already demonstrated the feasibility of large-scale, collaborative monitoring efforts. By leveraging low-cost sensors, these programs 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 organizations, 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, programs such as the Blue Planet Initiative and the 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

Low-cost technologies foster societal engagement by democratizing 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 programs using affordable sensors to monitor water quality or track coastal erosion empower stakeholders to take proactive measures in managing their local environments.

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 visualize and interact with marine data, making complex concepts more accessible. Moreover, citizen science programs 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 efforts (Merlino et al. 2023a).

By bridging the gap between scientific research and public engagement, low-cost technologies are driving a cultural shift toward greater stewardship of ocean resources. These efforts not only enhance the resilience of coastal communities but also contribute to achieving global sustainability goals by promoting informed and collaborative decision-making.

The engagement of local communities and the promotion of Ocean Literacy are increasingly recognized as fundamental components in enhancing the effectiveness and societal impact of low-cost marine observation technologies. Citizen science initiatives and do-it-yourself (DIY) 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 visualization tools, these 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).

Moreover, by fostering public awareness and strengthening the connection between scientific research and society, such participatory models encourage more inclusive and informed policymaking. However, to fully realize these benefits, it is essential to address key challenges related to data reliability, standardization, and scalability. Additionally, advocacy for inclusive education and the development of ethical guidelines must be prioritized to ensure responsible practices and to maximize both societal and environmental gains.

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. 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.

8.2 Recommendations for Policymakers and Researchers

• Invest in Research and Development: Allocate funding to enhance sensor accuracy, durability, and scalability to ensure their reliability and long-term usability in diverse marine environments.

• Promote Policy Support: Develop and implement policies that encourage the adoption and deployment of affordable technologies in marine observation networks. Adapt the call for tender rules to the purchase of such lower cost equipment.

• Foster Stakeholder Collaboration: Improve partnerships among governments, academic institutions, industry, and local communities to facilitate standardization, data sharing, and capacity building.

• Encourage Open Science: Support the creation of open-access platforms for data dissemination and analysis, ensuring that marine data is accessible to all stakeholders, including researchers, policymakers, and the public.

• Integrate Citizen Science: Leverage community-driven initiatives to expand observational coverage and enhance societal engagement in ocean research and conservation. Provide and long-term support data infrastructures to store, archive and visualise citizen science data.

• Expand Training Programs: Develop educational initiatives to train local communities and early-career researchers in deploying and maintaining low-cost technologies.

Foster Open Source Hardware by providing targeted funding, support standards development, and innovation programs; promote systematic publication of hardware designs; innovate in joint purchasing processes (investment of many units, each one under the usual accounting limit of consumables) and foster the formation of local communities of innovators.

8.3. Call to Action for Advancing Low-Cost Oceanography

The time is now to embrace low-cost technologies as a cornerstone of modern oceanography. Stakeholders must work together to overcome challenges and unlock the full potential of these innovative solutions. Collaborative efforts should prioritize the integration of advanced technologies, the harmonization of global observation systems, and the promotion of inclusive practices that engage diverse communities.

The potential of low-cost technologies extends beyond scientific research to societal resilience, offering tools to address environmental threats and improve disaster preparedness. By leveraging these tools, we can enhance our understanding of the oceans, mitigate environmental threats, and ensure the sustainable use of marine resources for future generations. Together, we can build a resilient, equitable, and sustainable future for the world’s oceans, where scientific discovery and societal progress go hand in hand.

Within Global Ocean Observing System 2030 Strategy, co-sponsored by IOC-UNESCO, innovation in observing technologies and networks is fundamental to develop an integrated, responsive and sustained global observing system. GOOS now needs to extend the measurement of EOVs from the open ocean into continental shelf and coastal systems, expanding spatial coverage of observing into coastal oceans, thus requiring additional technologies.

Since OceanObs’09, GOOS now also encompasses operational services and marine ecosystem health, from the open ocean into coastal environments where much of the world’s population resides.

EOVs discussion

Here, we delve into issues addressed in the **Coastal GOOS Strategy Document and Guidelines (2013)** and the **Global Ocean Observing System: 2030 Strategy (2019)**.

Regarding Essential Ocean Variables (EOVs), updated to 2023, they are defined in the **Global Climate Observing System (GCOS)**:

GCOS - Essential Climate Variables

These refer to the **2022 GCOS Implementation Plan (GCOS-244)**:

2022 GCOS Implementation Plan

Examples include: **Sea Level**, **Sea State**, **Marine Habitats**, **River Discharge**. All variables (e.g., **Particulate Matter**, **Nutrients**, **Oxygen**, and others) are included in the GOOS EOVs. The **EOV Specification Sheets** detail the differences between coastal and offshore variables:

GOOS EOV Framework.

For biological EOVs (e.g., **Benthos**, **Habitat**), reference should be made to the **Report of the First Workshop of Technical Experts for the Global Ocean Observing System (GOOS) Biology and Ecosystems Panel: Identifying Ecosystem Essential Ocean Variables (EOVs)** (2014):

Biology and Ecosystems Panel Report.

Another key document is **Requirements for Global Implementation of the Strategic Plan for Coastal GOOS** (2012):

Coastal GOOS Strategic Plan Requirements.

Finally, the presentation **Evaluating Coastal Observation Requirements and Implementation Globally** by J. Wilkin is highly informative and provides a more in-depth analysis of EOVs than the tables presented:

Evaluating Coastal Observation Requirements

References

Adade, R., Aibinu, A. M., Ekumah, B., & Asaana, J. (2021). Unmanned Aerial Vehicle (UAV) applications in coastal zone management—A review. Environmental Monitoring and Assessment, 193, 1-12.

AFNOR standard (2013) NF X 10-812 Marine environment – Oceanographic instrumentation – Guide for environmental tests. https://www.boutique.afnor.org/en-gb/standard/nf-x10812/ marine-environment-underwater-equipment-environment-tests-and-recommendatio/fa178382/41343

Ahmed, T., Creedon, L., & Gharbia, S. S. (2023). Low-Cost Sensors for Monitoring Coastal Climate Hazards: A Systematic Review and Meta-Analysis. Sensors, 23(3), 1717.

Albaladejo, C., Soto, F., Torres, R., Sánchez, P., & López, J. A. (2012). A low-cost sensor buoy system for monitoring shallow marine environments. Sensors, 12(7), 9613-9634.

Álvarez-Silva, Ó., Osorio, A. F., Quintero, D., Jaramillo, C., Bolaños, F., Osorio-Cano, J. D., & Suárez-Bustamante, F. A. (2023). Development and validation of a versatile low-cost instrument for monitoring water level in coastal applications: BlueLog. Journal of Coastal Conservation, 27(4), 30.

Aguzzi J., Chatzievangelou D., Robinson N.J., Bahamon N., Berry A., Carreras M., Company J. B., Costa C., del Rio Fernandez J., Falahzadeh A., Fifas S., Flögel S., Grinyó J., Jónasson J. P., Jonsson P., Lordan C., Lundy M., Marini S., Martinelli M., Masmitja I., Mirimin L., Naseer A., Navarro J., Palomeras N., Picardi G., Silva C., Stefanni S., Vigo M., Vila Y., Weetman A., Doyle J. Advancing fishery-independent stock assessments for the Norway lobster (Nephrops norvegicus) with new monitoring technologies. Frontiers in Marine Science, 9: 969071, https://doi.org/10.3389/fmars.2022.969071, 2022.

Arduino Project Hub. (n.d.). Retrieved from https://create.arduino.cc/projecthub

Aydoğdu A., Pinardi N., Pistoia J., Martinelli M., Belardinelli A., Sparnocchia S. Assimilation Experiments for the Fishery Observing System in the Adriatic Sea. Journal of Marine Systems 162:126-136, https://doi.org/10.1016/j.jmarsys.2016.03.002, 2016.

Banzi, M., & Shiloh, M. (2022). Getting started with Arduino: the open source electronics prototyping platform. Maker Media, Inc..

Batubara, M., Risandi, J., Sufyan, A., Pamungkas, A., Wardhani, K. S., Hendriyono, W., ... & Alfahmi, F. (2024, June). The application of a low-cost microcomputer logger with pressure-temperature based sensor for coastal observations: A preliminary study. In IOP Conference Series: Earth and Environmental Science (Vol. 1350, No. 1, p. 012034). IOP Publishing.

Beddows, P. A., & Mallon, E. K. (2018). Cave pearl data logger: a flexible arduino-based logging platform for long-term monitoring in harsh environments. Sensors, 18(2), 530.

Bittig, H. C., Körtzinger, A., Neill, C., van Ooijen, E., Plant, J. N., Hahn, J., ... & Johnson, K. S. (2018). Oxygen optode sensors: Principles and practice. Methods in Oceanography, 17, 1–25. https://doi.org/10.1016/j.mio.2018.09.002

Bingham Nicholas (2013) Designing pressure-tolerant electronic systems https://www.uutech.com/ptepaper/ - - Schmidt Ocean Institute

Bizer, C., Vidal, ME., Skaf-Molli, H. (2018). Linked Open Data. In: Liu, L., Özsu, M.T. (eds) Encyclopedia of Database Systems. Springer, New York, NY. https://doi.org/10.1007/978-1-4614-8265-9_80603

Blanco-Gómez, P., Jiménez-García, J. L., & Cecilia, J. M. (2023). Low-cost automated GPS, electrical conductivity and temperature sensing device (EC+ T Track) and Android platform for water quality monitoring campaigns. HardwareX, 13, e00381.

Bogdan, R., Paliuc, C., Crisan-Vida, M., Nimara, S., & Barmayoun, D. (2023). Low-cost internet-of-things water-quality monitoring system for rural areas. Sensors, 23(8), 3919.

Borisov, S. M., & Klimant, I. (2012). Optical sensors for dissolved oxygen: methods, applications, and new trends. Analytical and Bioanalytical Chemistry, 400(7), 2427–2441. https://doi.org/10.1007/s00216-011-5231-9

Bresnahan, P., Cyronak, T., Brewin, R. J., Andersson, A., Wirth, T., Martz, T., ... & Waters, S. (2022). A high-tech, low-cost, Internet of Things surfboard fin for coastal citizen science, outreach, and education. Continental Shelf Research, 242, 104748.

Briciu-Burghina, C., Power, S., Delgado, A., & Regan, F. (2023). Sensors for coastal and ocean monitoring. Annual Review of Analytical Chemistry, 16(1), 451-469.

Buck, J. J., Bainbridge, S. J., Burger, E. F., Kraberg, A. C., Casari, M., Casey, K. S., ... & Schewe, I. (2019). Ocean data product integration through innovation-the next level of data interoperability. Frontiers in Marine Science, 6, 32.

Butler, J., & Pagniello, C. M. (2021). Emerging, low-cost ocean observing technologies to democratize access to the ocean. Oceanography, 34(4), 94-95.

Camilli, R., Reddy, C. M., Yoerger, D. R., Van Mooy, B. A., Jakuba, M. V., Kinsey, J. C., ... & Maloney, J. V. (2010). Tracking hydrocarbon plume transport and biodegradation at Deepwater Horizon. Science, 330(6001), 201-204.

Campagnaro, F., Ghalkhani, M., Tumiati, R., Marin, F., Dal Grande, M., Pozzebon, A., ... & Zorzi, M. (2024). Monitoring the Venice Lagoon: An IoT Cloud-Based Sensor Network Approach. IEEE Journal of Oceanic Engineering.

Cavanaugh, K. C., Bell, T. W., Aerni, K. E., Byrnes, J. E., McCammon, S., & Smith, M. M. (2024). New Technologies for Monitoring Coastal Ecosystem Dynamics. Annual Review of Marine Science, 17.

Carminati, M., Stefanelli, V., Luzzatto-Fegiz, P., 2016. Micro-USB Connector Pins as Low-Cost, Robust Electrodes for Microscale Water Conductivity Sensing in Oceanographic Research. *Procedia Engineering*, 168, 407-410.

Carpi, P., Martinelli, M., Belardinelli, A., Russo, A., Arneri, E., Coluccelli, A., and Santojanni, A.: Coupling an oceanographic model to a Fishery Observing System through mixed models: the importance of fronts for anchovy in the Adriatic Sea, Fish. Oceanogr., 24, 521–532, https://doi.org/10.1111/fog.12126, 2015.

Centenaro, M., Costa, C. E., Granelli, F., Sacchi, C., Vangelista, L. (2021). A survey on technologies, standards and open challenges in satellite IoT. In IEEE Communications Surveys and Tutorials (Vol. 23, Issue 3, pp. 1693–1720). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/COMST.2021.3078433

Chandrappa, S., Dharmanna, L., Shyama Srivatsa Bhatta, U. V., Sudeeksha Chiploonkar, M., Suraksha, M. N., & Thrupthi, S. (2017). Design and development of IoT device to measure quality of water. International Journal of Modern Education and Computer Science (IJMECS), 9(4), 50-56.

Chiarini, M., Guicciardi, S., Angelini, S., Tuck, I. D., Grilli, F., Penna, P., Domenichetti, F., Canduci, G., Belardinelli, A., Santojanni, A., Arneri, E., Milone, N., Medvešek, D., Isajlovi´c, I., Vrgoˇc, N., and Martinelli, M.: Accounting for environmental and fishery management factors when standardising CPUE data from a scientific survey: A case study for Nephrops norvegicus in the Pomo Pits area (Central Adriatic Sea), PLoS ONE, 17, e0270703, https://doi.org/10.1371/journal.pone.0270703, 2022.

Cocker, E., Bert, J. A., Torres, F., Shreve, M., Kalb, J., Lee, J., Poimboeuf, M., Fautley, P., Adams, S., Lee, J., Lu, J., Chua, C., Chang, N., Neltner, S., Gray, M. (2022). Low-Cost, Intelligent Drifter Fleet for Large-Scale, Distributed Ocean Observation.

Collins, C. O., Dickhudt, P., Thomson, J., de Paolo, T., Otero, M., Merrifield, S., ... & Centurioni, L. (2024). Performance of moored GPS wave buoys. Coastal Engineering Journal, 66(1), 17-43.

Contreira-Pereira Leonardo, Yücel Mustapha, Omanovic Dario, Brulport Jean-Pierre, Le Bris Nadine (2013)- Silver-Based Electrochemical Sensors For Autonomous Monitoring . Deep Sea Research Part I: Oceanographic Research Papers,volume 80, p 47-57, https://doi.org/10.1016/j.dsr.2013.05.014

Copernicus Marine Environment Monitoring Service (marine.copernicus.eu).

Coppola, L., Ntoumas, M., Bozzano, R., Bensi, M., Hartman, S. E.,Charcos Llorens, Mi., Craig, J., Rolin, J-F., Giovanetti, G., Cano, D., Karstensen, J., Cianca, A., Toma, D., Stasch, C., Pensieri, S., Cardin, V., Tengberg, A., Petihakis, G., Cristini, L. (2016) Handbook of best practices for open ocean fixed observatories. European Commission, FixO3 Project, 127pp. (European Commission, FixO3 project, FP7 Programme 2007-2013 under grant agreement n° 312463). DOI: https://doi.org/10.25607/OBP-1488

Crise, A., Ribera d'Alcalà, M., Mariani, P., Petihakis, G., Robidart, J., Iudicone, D., ... & Malfatti, F. (2018). A conceptual framework for developing the next generation of Marine OBservatories (MOBs) for science and society. Frontiers in Marine Science, 5, 318.

Cristini, L., Lampitt, R.S., Cardin, V., Delory, E., Haugan, P., O'Neill, N., Petihakis, G., Ruhl, H.A. (2016). Cost and value of multidisciplinary fixed-point ocean observatories. Mar. Policy, 71, 138-146.

de Camargo, E. T., Spanhol, F. A., Slongo, J. S., da Silva, M. V. R., Pazinato, J., de Lima Lobo, A. V., ... & Martins, L. D. (2023). Low-cost water quality sensors for IoT: A systematic review. Sensors, 23(9), 4424.

Crombie, D. D.: Doppler Spectrum of Sea Echo at 13.56 Mc./s., Nature, 175, 681–682, 1955.

Danovaro, R., Carugati, L., Berzano, M., Cahill, A. E., Carvalho, S., Chenuil, A., Corinaldesi, C., Cristina, S., David, R., Dell'Anno, A., Dzhembekova, N., Garcés, E., Gasol, J. M., Goela, P., Férial, J.-P., Ferrera, I., Forster, R. M., Kurekine, A. A., Rastelli, E., Marinova, V., Miller, P. I., Moncheva, S., Newton, A., Pearman, J. K., Pitois, S. G., Reñé, A., Rodríguez-Ezpeleta, N., Saggiomo, V., Simis, S. G. H., Stefanova, K., Wilson, C., Lo Martire, M., Greco, S., Cochran, S. K. J., Mangoni, O., and Borja, A. (2016). Implementing and Innovating Marine Monitoring Approaches for Assessing Marine Environmental Status. Front. Mar. Sci., 3:213. doi: 10.3389/fmars.2016.00213.

Davidson F, Alvera-Azcárate A, Barth A, Brassington GB, Chassignet EP, Clementi E, De Mey-Frémaux P, Divakaran P, Harris C, Hernandez F, Hogan P, Hole LR, Holt J, Liu G, Lu Y, Lorente P, Maksymczuk J, Martin M, Mehra A, Melsom A, Mo H, Moore A, Oddo P, Pascual A, Pequignet A-C , Kourafalou V, Ryan A, Siddorn J, Smith G, Spindler D, Spindler T, Stanev EV, Staneva J, Storto A, Tanajura C, Vinayachandran PN, Wan L, Wang H, Zhang Y, Zhu X and Zu Z (2019) Synergies in Operational Oceanography: The Intrinsic Need for Sustained Ocean Observations. Front. Mar. Sci. 6:450. doi: 10.3389/fmars.2019.00450

Deschner et al 2024 https://doi.org/10.3389/fmars.2024.1450207

Dominguez-Carrió Carlos, Fontes Jorge, Morato Telmo. (2021) A cost-effective video system for a rapid appraisal of deep-sea benthic habitats: The Azor drift-cam. British Ecological Society -Practical tools. https://doi.org/10.1111/2041-210X.13617

Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P., Eguiluz, V. M., ... & Juanes, F. (2021). The soundscape of the Anthropocene ocean. Science, 371(6529), eaba4658.

EOOS Technology Forum Report 2024. EuroGOOS publication, 2025. Brussels, Belgium

Formel, N., Enochs, I. C., Sinigalliano, C., Anderson, S. R., & Thompson, L. R. (2021). Subsurface automated samplers for eDNA (SASe) for biological monitoring and research. HardwareX, 10, e00239.

Frank-Comas, A., Puigdefàbregas, J., Tomàs-Ferrer, J., Font, A., Agulles, M., Soto-Navarro, J., Gomis, D., Villalonga, J., Ramos, J., Melo, C, and Jordà, G. Implementation of a Low-Cost Ultra-Dense Tide Gauge Network in the Balearic Islands, 9th International Workshop on Marine Technology (MARTECH 2021). Instrumentation Viewpoint, 2021, núm. 21, p. 85, ISSN 1886-4864.

Garcia-Soto, C., van der Meeren, G. I., Busch, J. A., Delany, J., Domegan, C., Dubsky, K., Fauville, G., Gorsky, G. von Juterzenka, K., Malfatti, F., Mannaerts, G., McHugh, P., Monestiez, P., Seys, J., Węsławski, J.M. & Zielinski, O. (2017) Advancing Citizen Science for Coastal and Ocean Research. French, V., Kellett, P., Delany, J., McDonough, N. [Eds.] Position Paper 23 of the European Marine Board, Ostend, Belgium. 112pp. ISBN: 978-94-92043-30-6

George, S. D., Sepulveda, A. J., Hutchins, P. R., Pilliod, D. S., Klymus, K. E., Thomas, A. C., ... & Leinonen, E. G. (2024). Field Trials of an Autonomous eDNA Sampler in Lotic Waters. Environmental Science & Technology, 58(47), 20942-20953.

Gillett, D., & Marchiori, A. (2019). A low-cost continuous turbidity monitor. Sensors, 19(14), 3039.

Giugliano, R., Casani, C., Locritani, M., Palleschi, V., Poggialini, F., Cocciaro, B., Ricci, L., Bronco, S., De Monte,C., Arrighetti, L., Vivaldi, B., Di VS. and Merlino, S. (2025). Italian Pellets Watch: First step towards national assessment of resin pellets distribution, characterization and pollutants absorption. Environmental Research, Volume 278, 2025,121644, https://doi.org/10.1016/j.envres.2025.121644.

González-Nuevo, G., Gago, J., and Cabanas, J. M.: Upwelling Index: A powerful tool for marine research in the NW Iberian upwelling system, J. Oper. Oceanogr., 7, 47–57, 2014.

Green, D. R., Hagon, J. J., Gómez, C., & Gregory, B. J. (2019). Using low-cost UAVs for environmental monitoring, mapping, and modelling: Examples from the coastal zone. In Coastal management (pp. 465-501). Academic Press.

Gu, H., Zhu, X., Shan, R., Zang, J., Qian, L. andi Lin, P. Evaluation of a GNSS for wave measurement and directional wave spectrum analysis, Ocean Engineering, Volume 270, 2023, 113683, ISSN 0029-8018, https://doi.org/10.1016/j.oceaneng.2023.113683.

Hendricks, A., Mackie, C. M., Luy, E., Sonnichsen, C., Smith, J., Grundke, I., ... & Sieben, V. (2023). Compact and automated eDNA sampler for in situ monitoring of marine environments. Scientific Reports, 13(1), 5210.

Hildebrand, J. A. (2009). Anthropogenic and natural sources of ambient noise in the ocean. Marine Ecology Progress Series, 395, 5-20.

Hirose, N., Takikawa, T., Ito, T., Nagamoto, A., Takagi, N., Kokubo, T., Kimura, M., Yabuki, T., Hazama, T.: Positive data circulation established by Kyushu Smart Fisheries (QSF) team, Front. Mar. Sci., 11, https://doi.org/10.3389/fmars.2024.1457272, 2024.

Holgate, S.J., Matthews, A., Woodworth,P.L., Rickards, L.J., Tamisiea, M.E, Bradshaw, E., Foden, P.R., Gordon, K.M., Jevrejeva, S. and Pugh, J. 2013 New Data Systems and Products at the Permanent Service for Mean Sea Level. Journal of Coastal Research: Volume 29, Issue 3: pp. 493 – 504. doi:10.2112/JCOASTRES-D-12-00175.1.

Hussain, I., Das, M., Ahamad, K.U., Nath, P., 2017. Water salinity detection using a smartphone. Sensors and Actuators B: Chemical, 239, 1042-1050 IOC (2025), https://oceandecade.org/ocean-decade-corporate-data-group/

Jakoboski, J., Roughan, M., Radford, J., Azevedo Correia de Souza, J.M., Felsing, M., Smith, R., Puketapu-Waite, N., Montaño Orozco, M., Maxwell, K.H., Van Vranken C.: Partnering with the commercial fishing sector and Aotearoa New Zealand's ocean community to develop a nationwide subsurface temperature monitoring program, Progress in Oceanography, 225, 103278, https://doi.org/10.1016/j.pocean.2024.103278, 2024.

Janzen, C., McCammon, M., Weingartner, T., Statscewich, H., Winsor, P., Danielson, S., & Heim, R. (2019). Innovative real-time observing capabilities for remote coastal regions. Frontiers in Marine Science, 6, 176.

Kapsenberg L, Bockmon EE, Bresnahan PJ, Kroeker KJ, Gattuso J-P and Martz TR (2017) Advancing Ocean Acidification Biology Using Durafet® pH Electrodes. Front. Mar. Sci. 4:321. doi: 10.3389/fmars.2017.00321

Kaufman, D. E., Friedrichs, M. A. M., Hemmings, J. C. P., and Smith Jr., W. O.: Assimilating bio-optical glider data during a phytoplankton bloom in the southern Ross Sea, Biogeosciences, 15, 73–90, https://doi.org/10.5194/bg-15-73-2018, 2018.

Kelly, R., Fleming, A., Pecl, G. T., von Gönner, J., & Bonn, A. (2020). Citizen science and marine conservation: a global review. Philosophical Transactions of the Royal Society B, 375(1814), 20190461.

Kerry, C., Roughan, M., & Azevedo Correia de Souza, J. M.: Assessing the impact of subsurface temperature observations from fishing vessels on temperature and heat content estimates in shelf seas: a New Zealand case study using Observing System Simulation Experiments. Frontiers in Marine Science, 11, https://doi.org/10.3389/fmars.2024.1358193, 2024.

Kinar, N.J., Brinkmann, M. Development of a sensor and measurement platform for water quality observations: design, sensor integration, 3D printing, and open-source hardware. Environ Monit Assess 194, 207 (2022). https://doi.org/10.1007/s10661-022-09825-9

Kinsey, J. C., Yoerger, D. R., Jakuba, M. V., Camilli, R., Fisher, C. R., & German, C. R. (2011, September). Assessing the deepwater horizon oil spill with the sentry autonomous underwater vehicle. In 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (pp. 261-267). IEEE.

Koepp, J., Mahmud, N., Bues, D, Mandel, A. (2018). Characterization of Sigfox Devices from Lab to Production Line. (Application Note 2.2018 – 1MA294_2e). Retrieved from Rohde & Schwarz website: https://scdn.rohde-schwarz.com/ur/pws/dl_downloads/dl_application/application_notes/1ma294/1MA294_3e_Sigfox_Device_Test.PDF

Kröger S., Parker E. R., Metcalfe J. D., Greenwood N., Forster R. M., Sivyer D. B., and Pearce D. J., "Sensors for observing ecosystem status," Ocean Sci., vol. 5, pp. 523-535, 2009.

Langenkämper, D., Van Kevelaer, R., Purser, A., & Nattkemper, T. W. (2020). Gear-induced concept drift in marine images and its effect on deep learning classification. Frontiers in Marine Science, 7, 506.

Lago, V., Roughan, M., Kerry, C., Knuckey, I.: Fishing for Ocean Data in the East Australian Current, Oceanography, 38 (1), https://doi.org/10.5670/oceanog.2025e105, 2025.

Levin Lisa A. , Bett Brian J. , Gates Andrew R. , Heimbach Patrick , Howe Bruce M. , Janssen Felix , McCurdy Andrea , Ruhl Henry A. , Snelgrove Paul , Stocks Karen I. , Bailey David , Baumann-Pickering Simone , Beaverson Chris , Benfield Mark C. , Booth David J. , Carreiro-Silva Marina , Colaço Ana , Eblé Marie C. , Fowler Ashley M. , Gjerde Kristina M. , Jones Daniel O. B. , Katsumata K. , Kelley Deborah , Le Bris Nadine , Leonardi Alan P. , Lejzerowicz Franck , Macreadie Peter I. , McLean Dianne , Meitz Fred , Morato Telmo , Netburn Amanda , Pawlowski Jan , Smith Craig R. , Sun Song , Uchida Hiroshi , Vardaro Michael F. , Venkatesan R. , Weller Robert A. (2019) Global Observing Needs in the Deep Ocean. Frontiers in Marine Science – VOLUME 6 , DOI=10.3389/fmars.2019.00241 - ISSN=2296-7745

Lindstrom, E., J. Gunn, A. Fischer, A. McCurdy, and L.K. Glover 2012. A Framework for Ocean Observing. Prepared by the Task Team for an Integrated Framework for Sustained Ocean Observing (IFSOO), Report IOC/INF-1284 Rev., UNESCO, Paris, 28 pp.

Lissenden, J., Maley, S. and Mehta, K. (2014). An Era of Appropriate Technology: Evolutions, Oversights and Opportunities. Journal of Humanitarian Engineering. 3. 10.36479/jhe.v3i1.34.

Liu, Y., Li, M., Liu, Y., Wang, Y., Jiang, S., Wang, Y., Tian, L. and Qiao, F. Real-time precise measurements of ocean surface waves using GNSS variometric approach, International Journal of Applied Earth Observation and Geoinformation, Volume 115, 103125, ISSN 1569-8432, https://doi.org/10.1016/j.jag.2022.103125., 2022.

Liu, L., Liu, R., Ma, G., Feng, S., Mu, Y., Meng, D., ... & Cai, E. (2023). Online Monitoring of Seawater Carbon Dioxide Based on an Infrared Rear Beam Splitter. Sensors, 23(14), 6273.

Lockridge, G., Dzwonkowski, B., Nelson, R., & Powers, S. (2016). Development of a low-cost arduino-based sonde for coastal applications. Sensors, 16(4), 528.

Lorente, P., Rubio, A., Reyes, E., Solabarrieta, L., Piedracoba, S., Tintoré, J., and Mader, J.: High-frequency radar-derived coastal upwelling index, in: 7th edition of the Copernicus Ocean State Report (OSR7), edited by: von Schuckmann, K., Moreira, L., Le Traon, P.-Y., Grégoire, M., Marcos, M., Staneva, J., Brasseur, P., Garric, G., Lionello, P., Karstensen, J., and Neukermans, G., Copernicus Publications, State Planet, 1-osr7, 8, https://doi.org/10.5194/sp-1-osr7-8-2023, 2023.

Lucchetti A., Belardinelli A., D'Andrea L., Marčeta B., Martinelli M., Russo T., Keč V.Č., Zorica B., Virgili M. Small pelagic purse seines in the Adriatic Sea: A spatial analysis and technical overview in relation to Mediterranean Regulation provisions. Marine Policy 98: 104-114, https://doi.org/10.1016/j.marpol.2018.09.031, 2018.

Lumpkin, R., Özgökmen, T., Centurioni, L., 2017. Advances in the application of surface drifters. Annual Review of Marine Science, 9, 59-81.

McMahon, C.R. and Roquet, F.: Animal-Borne Ocean Sensors: A Decadal Vision Through New Eyes, Marine Technology Society Journal, Number 3, May/June 2022, pp. 36-38(3), 2022, doi:10.4031/MTSJ.56.3.2

McMahon Clive R. , Roquet Fabien , Baudel Sophie , Belbeoch Mathieu , Bestley Sophie , Blight Clint, Boehme Lars , Carse Fiona , Costa Daniel P. , Fedak Michael A. , Guinet Christophe , Harcourt Robert, Heslop Emma , Hindell Mark A. , Hoenner Xavier , Holland Kim , Holland Mellinda , Jaine Fabrice R. A. , Jeanniard du Dot Tiphaine , Jonsen Ian , Keates Theresa R. , Kovacs Kit M. , Labrousse

Manning, J., & Pelletier, E. Environmental monitors on lobster traps (eMOLT): long-term observations of New England's bottom-water temperatures. Journal of Operational Oceanography, 2(1), 25–33. https://doi.org/10.1080/1755876X.2009.11020106, 2009.

Marcelli, M., Piermattei, V., Madonia, A., & Mainardi, U. (2014). Design and application of new low-cost instruments for marine environmental research. Sensors, 14(12), 23348-23364.

Marcelli, M., Piermattei, V., Madonia, A., Lacava, T., & Mainardi, U. (2016). T-FLaP advances: Instrumental and operative implementation. Journal of Operational Oceanography, 9(sup1), s185-s192.

Marcelli, M., Piermattei, V., Gerin, R., Brunetti, F., Pietrosemoli, E., Addo, S. A. M., ... & Crise, A. (2021). Toward the widespread application of low-cost technologies in coastal ocean observing (Internet of Things for the Ocean).

March, D., Boehme, L., Tintoré, J., Vélez-Belchi, P.J. and Godley, B.J.: Towards the integration of animal-borne instruments into global ocean observing systems, Global Change Biology, Volume 26, Issue 2, Pages 586-596, doi: 10.1111/gcb.14902, 2020.

Mariani, P., Bachmayer, R., Kosta, S., Pietrosemoli, E., Ardelan, M. V., Connelly, D. P., ... & Crise, A. (2021). Collaborative automation and IoT technologies for coastal ocean observing systems. Frontiers in Marine Science, 8, 647368.

Martinelli M., Guicciardi S., Penna P., Belardinelli A., Croci C., Domenichetti F., Santojanni A., Sparnocchia S. Evaluation of the oceanographic measurement accuracy of different commercial sensors to be used on fishing gears. Ocean Engineering 111: 22–33,https://doi.org/10.1016/j.oceaneng.2015.10.037, 2016.

Martinelli, M., Belardinelli, A., Penna, P., Croci, C., Domenichetti, F., Campanelli, A., Betti, M., Paschini, E., Sparnocchia, S., & Guicciardi, S. : NEXOS Validation report, for Deliverable 8.2: 5.6 Fishing vessel and EAF.4/EAF.6 sensors. In Work Package 8 – Deliverable 8.2 – Validation Report – FP7 Ocean 2013 NeXOS project "Next generation Low-Cost Multifunctional Web Enabled Ocean Sensor Systems Empowering Marine, Maritime and Fisheries Management." https://archimer.ifremer.fr/doc/00630/74255/73886.pdf, 2017.

Martinelli M., Penna P., Guicciardi S., Duchene J., Haavisto N., Marty S., King A., Van Bavel B., Ødegaard Ø., Ntoumas M., Campanelli A., David A., Domenichetti F., Le Gall C., Lescroart E., Malardé D., Moro F., Kielosto S., Seppälä J., Sparnocchia S., Zacchetti NAUTILOS D5.6 - Validation and integration report on ships of opportunity. Zenodo, https://doi.org/10.5281/zenodo.10665503, 2023a.

Martinelli M., Duchêne J., Malardé D., Marty S., King A.L., Ntoumas M., Smerdon A., Novellino A., Pieri G. NAUTILOS Fisheries and Aquaculture Observing Systems. Abstract Number: 5892 Session: SS042 Fishing4Data: Fishing Gear as an Oceanographic Data Collection Platform. ASLO 2023 Aquatic Sciences Meeting to be held 4–9 June 2023 in Palma de Mallorca, Spain. https://aslo.secure-platform.com/2023/solicitations/12/sessiongallery/864/application/5892, 2023b.

Martinelli, M., Duchene, J., King, A., Marty, S., Ntoumas, M., Berghöfer, E., Alonso, I., Penna, P., Moro, F., Zacchetti, L., Cecapolli, E., DOMENICHETTI, F., Le Gall, C., Malardé, D., Misurale, F., & Smerdon, A. NAUTILOS D7.1 - Fisheries and Aquaculture Observing Systems demonstration mid-term. Zenodo, 2024. https://doi.org/10.5281/zenodo.14260995

Matos, T., Faria, C. L., Martins, M. S., Henriques, R., Gomes, P. A., & Goncalves, L. M. (2019). Development of a cost-effective optical sensor for continuous monitoring of turbidity and suspended particulate matter in marine environment. Sensors, 19(20), 4439.

McKee, D. C., Doney, S. C., Della Penna, A., Boss, E. S., Gaube, P., Behrenfeld, M. J. (2023). Biophysical Dynamics at Ocean Fronts Revealed by Bio-Argo Floats. Journal of Geophysical Research-Biogeosciences. 128: | DOI:10.1029/2022JC019226

Mekki, K., Bajic, E., Chaxel, F., Meyer, F. (2018). Overview of Cellular LPWAN Technologies for IoT Deployment: Sigfox, LoRaWAN, and NB-IoT. 2018 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops), 197–202. https://doi.org/10.1109/PERCOMW.2018.8480255

Merlino ,S.;Paterni,M.; Locritani, M.; Andriolo, U.; Gonçalves, G.; Massetti, L. Citizen Science for Marine Litter Detection and Classification on Unmanned Aerial Vehicle Images. (2021) Water, 13, 3349. https://doi.org/10.3390/ w13233349

Merlino, S., Locritani, M., Guarnieri, A., Delrosso, D., Bianucci, M., Paterni, M. (2023). Marine Litter Tracking System: A Case Study with Open-Source Technology and a Citizen Science-Based Approach. Sensors, 23, 935. https://doi.org/10.3390/s23020935

Merlino, S.; Calabrò, V.; Giannelli, C.; Marini, L.; Pagliai, M.; Sacco, L.; Bianucci, M. (2023). The Smart Drifter Cluster: Monitoring Sea Currents and Marine Litter Transport Using Consumer IoT Technologies. Sensors, 23, 5467. https:// doi.org/10.3390/s23125467

Metfies, K., Hessel, J., Klenk, R., Petersen, W., Wiltshire, K. H., & Kraberg, A. (2020). Uncovering the intricacies of microbial community dynamics at Helgoland Roads at the end of a spring bloom using automated sampling and 18S meta-barcoding. Plos one, 15(6), e0233921.

Miloslavich, P., Bax, N. J., Simmons, S. E., Klein, E., Appeltans, W., Aburto-Oropeza, O., ... & Shin, Y. J. (2018). Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. Global change biology, 24(6), 2416-2433.

Miloslavich, P., O'Callaghan, J., Heslop, E., McConnell, T., Heupel, M., Satterthwaite, E., Lorenzoni, L., Schloss, I., Belbeoch, M., Rome, N., Widdicombe, S., Olalekan Elegbede, I. & Fontela, M. (2024). Ocean Decade Vision 2030 White Papers – Challenge 7: Sustainably Expand the Global Ocean Observing System. Paris, UNESCO-IOC. (The Ocean Decade Series, 51.7.). https://doi.org/10.25607/brxb-kr45

Mishra, J. P., Singh, K., & Chaudhary, H. (2023). Research advancements in ocean environmental monitoring systems using wireless sensor networks: a review. TELKOMNIKA (Telecommunication Computing Electronics and Control), 21(3), 513-527.

Murphy, K., Heery, B., Sullivan, T., Zhang, D., Paludetti, L., Lau, K. T., ... & Regan, F. (2015). A low-cost autonomous optical sensor for water quality monitoring. Talanta, 132, 520-527.

Murphy, K., Sullivan, T., Heery, B., & Regan, F. (2015). Data analysis from a low-cost optical sensor for continuous marine monitoring. Sensors and Actuators B: Chemical, 214, 211-217.

Motsenbocker Breanna E., Noyes Timothy J., Runyan, Alexandra T. Shomberg Russell and Phillips Brennan T. (2024) A liquid-filled camera for low-cost imaging in the deep sea, Deep Sea Research Part I: Oceanographic Research Papers, 206, p 104-263, {https://doi.org/10.1016/j.dsr.2024.104263}.

Možek, M.; Pečar, B.; Vrtačnik, D. Cost-Efficient Oceanographic Instrument with Microfabricated Sensors for Measuring Conductivity, Temperature and Depth of Seawater. Sensors 2024, 24, 3940. https://doi.org/10.3390/s24123940

Nieto-Mora, D. A., Rodríguez-Buritica, S., Rodríguez-Marín, P., Martínez-Vargaz, J. D., & Isaza-Narváez, C. (2023). Systematic review of machine learning methods applied to ecoacoustics and soundscape monitoring. Heliyon, 9(10).

Ollitrault Michel, Auffret Yves, Cortes Norbert, Hemon Catherine, Jegou Paul, Le Reste Serge, Loaec Gerard, Rannou Jean Philippe (1995). The SAMBA experiment. Volume 1 : SAMBA 1 LAGRANGIAN and CTD DATA. February 1994 -August 1995. Repères océans. (12), https://archimer.ifremer.fr/doc/00238/34946/

Nalakurthi, N. V. S. R., Abimbola, I., Ahmed, T., Anton, I., Riaz, K., Ibrahim, Q., ... & Gharbia, S. (2024). Challenges and Opportunities in Calibrating Low-Cost Environmental Sensors. Sensors, 24(11), 3650.

Newman, L., Heil, P., Trebilco, R., Katsumata, K., Constable, A., Van Wijk, E., ... & Spreen, G. (2019). Delivering sustained, coordinated, and integrated observations of the Southern Ocean for global impact. *Frontiers in Marine Science*, *6*, 433.

Novelli, G., Guigand, C. M., Boufadel, M. C., & Özgökmen, T. M. (2020). On the transport and landfall of marine oil spills, laboratory and field observations. Marine pollution bulletin, 150, 110805.

Oppenheimer, M. et al., 2019: Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate[Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N. Weyer (eds.)]. In Press, pp. 321–445, www.ipcc.ch/srocc/chapter/chapter-4-sea-level-rise-and-implications-for-low-lying-islands-coasts-and-communities/.

Palmer, M. R., Shagude, Y. W., Roberts, M. J., Popova, E., Wihsgott, J. U., Aswani, S., ... & Sekadende, B. (2021). Marine robots for coastal ocean research in the Western Indian Ocean. Ocean & Coastal Management, 212, 105805.

Patti, B., Martinelli, M., Aronica, S., Belardinelli, A., Penna, P., Bonanno, A., Basilone, G., Fontana, I., Giacalone, G., Gabriele Gallì, N., Sorgente, R., Angileri, I. V. M., Croci, C., Domenichetti, F., Bonura, D., Santojanni, A., Sparnocchia, S., D'Adamo, R., Marini, M., … Mazzola, S.: The fishery and oceanography observing system (FOOS): A tool for oceanography and fisheries science. Journal of Operational Oceanography, 9, S99–S118. https://doi.org/10.1080/1755876X.2015.1120961, 2016.

Parra, L., Viciano-Tudela, S., Carrasco, D., Sendra, S., & Lloret, J. (2023). Low-cost microcontroller-based multiparametric probe for coastal area monitoring. Sensors, 23(4), 1871.

Penna, P., Domenichetti, F., Belardinelli, A., and Martinelli, M.: Dataset of depth and temperature profiles obtained from 2012 to 2020 using commercial fishing vessels of the AdriFOOS fleet in the Adriatic Sea, Earth Syst. Sci. Data, 15, 3513–3527, https://doi.org/10.5194/essd-15-3513-2023, 2023.

Pearce, J. M. (2012). Building research equipment with free, open-source hardware. Science, 337(6100), 1303–1304. https://doi.org/10.1126/science.1228183

Pérez Gómez, B., Vilibić, I., Šepić, J., Međugorac, I., Ličer, M., Testut, L., Fraboul, C., Marcos, M., Abdellaoui, H., Álvarez Fanjul, E., Barbalić, D., Casas, B., Castaño-Tierno, A., Čupić, S., Drago, A., Fraile, M. A., Galliano, D. A., Gauci, A., Gloginja, B., Martín Guijarro, V., Jeromel, M., Larrad Revuelto, M., Lazar, A., Keskin, I. H., Medvedev, I., Menassri, A., Meslem, M. A., Mihanović, H., Morucci, S., Niculescu, D., Piermattei, V., Madonia, A., Bonamano, S., Martellucci, R., Bruzzone, G., Ferretti, R., ... & Marcelli, M. (2018). Cost-effective technologies to study the arctic ocean environment. Sensors, 18(7), 2257.

Piechaud, N., Hunt, C., Culverhouse, P. F., Foster, N. L., & Howell, K. L. (2019). Automated identification of benthic epifauna with computer vision. Marine Ecology Progress Series, 615, 15-30.

Pieri G, Ntoumas M, Martinelli M, Chatzinikolaou E, Martins F, Novellino A, Dimitrova N, Keller K, King A, Smerdon A, Mazza M, Malardé D, Cocco M, Torres A, Triantafyllou G, Sá S, Bebianno M J, Sparnocchia S, Kristiansen T, Lusher A: New technology improves our understanding of changes in the marine environment. 9th EuroGOOS International conference, Shom; Ifremer; EuroGOOS AISBL, May 2021, Brest, France. pp. 500-508. https://hal.science/hal-03329200v2

Popper, A. N., & Hastings, M. C. (2009). The effects of anthropogenic sources of sound on fishes. Journal of fish biology, 75(3), 455-489.

Poulain, P. M., Bussani, A., Gerin, R., Jungwirth, R., Mauri, E., Menna, M., & Notarstefano, G. (2013). Mediterranean surface currents measured with drifters: From basin to subinertial scales. Oceanography, 26(1), 38-47.

Quijano de Benito, J. M., Pascual, J., Palazov, A., Picone, M., Raicich, F., Said, M., Salat, J., Sezen, E., Simav, M., Sylaios, G., Tel, E., Tintoré, J., Zaimi, K., and Zodiatis, G.: Coastal sea level monitoring in the Mediterranean and Black seas, Ocean Sci., 18, 997–1053, https://doi.org/10.5194/os-18-997-2022, 2022.

Riser, S. C., Freeland, H. J., Roemmich, D., Wijffels, S., Troisi, A., Belbéoch, M., ... & Jayne, S. R. (2016). Fifteen years of ocean observations with the global Argo array. Nature Climate Change, 6(2), 145-153.

Rabello, J. R., Gonzáles, J. M., Batista, J. R., Silva, A. C., & Costa, E. J. (2021). A Simple, Effective, and Low-Cost System for Water Monitoring in Remote Areas Using Optical and Conductivity Data Signature. Water, Air, & Soil Pollution, 232, 1-13.

REGULATION (EU) No 1380/2013 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC.

Richardson, M., & Wallace, S. (2014). Getting Started with Raspberry Pi: Electronic Projects with Python, Scratch, and Linux. Maker Media, Inc..

Richardson, W. J., & Würsig, B. (1997). Influences of man-made noise and other human actions on cetacean behaviour. Marine & Freshwater Behaviour & Phy, 29(1-4), 183-209.

Roarty, H., Cook, T., Hazard, L., Harlan, J., Cosoli, S., Wyatt, L., Fanjul, E. A., Terrill, E., Otero, M., Largier, J., Glenn, S., Ebuchi, N., Whitehouse, B., Bartlett, K., Mader, J., Rubio, A., Corgnati, L. P., Mantovani, C., Griffa, A., Reyes, E., Lorente, P., FloresVidal, X., Rogowski, P., Prukpitikul, S., Lee, S. H., Lai, J. W., Guerin, C., Sanchez, J., Hansen, B., Grilli, S. and Matta, K. S.: The Global High Frequency Radar Network, Front. Mar. Sci., 6, 164, https://doi.org/10.3389/fmars.2019.00164, 2019.

Roemmich, D., Johnson, G.C., Riser, S., Davis, R., Gilson, J. et. al. 2009. The Argo Program: Observing the global ocean with profiling floats. Oceanography, 22 (2), 34-43.

Rudnick, D., Costa, D., Johnson, K., Lee, C., Timmermans, M.L., 2018 (January). ALPS II-Autonomous Platforms and Sensors. A Report of the ALPS II Workshop. In: ALPS II Workshop.

Russo T., D'Andrea L., Parisi A., Martinelli M., Belardinelli A., Boccoli F., Cignini I., Tordoni M., Cataudella S., Assessing the fishing footprint using data integrated from different tracking devices: Issues and opportunities, Ecological Indicators 69:818-827, https://doi.org/10.1016/j.ecolind.2016.04.043, 2016.

Russo T., Pulcinella J., Parisi A., Martinelli M., Belardinelli A., Santojanni A., Cataudella S., Colella S., Anderlini L. Modelling the strategy of mid-water trawlers targeting small pelagic fish in the Adriatic Sea and its drivers, Ecological Modelling 300: 102-113, https://doi.org/10.1016/j.ecolmodel.2014.12.001, 2015.

Sanchez-Iborra, R., Cano, M. D. (2016). State of the art in LP-WAN solutions for industrial IoT services. In Sensors (Switzerland) (Vol. 16, Issue 5). MDPI AG. https://doi.org/10.3390/s16050708

Sandahl, A., & Tøttrup, A. P. (2020). Marine citizen science: recent developments and future recommendations. Citizen Science: Theory and Practice, 5(1).

Sara , Lovell Philip , Lydersen Christian , March David , Mazloff Matthew , McKinzie Megan K. , Muelbert Mônica M. C. , O'Brien Kevin , Phillips Lachlan , Portela Esther , Pye Jonathan , Rintoul Stephen , Sato Katsufumi , Sequeira Ana M. M. , Simmons Samantha E. , Tsontos Vardis M. , Turpin Victor , van Wijk Esmee , Vo Danny , Wege Mia , Whoriskey Frederick Gilbert , Wilson Kenady , Woodward Bill. (2021) Animal Borne Ocean Sensors. AniBOS – An Essential Component of the Global Ocean Observing System. Front. Mar. Sci., 05 November 2021 | https://doi.org/10.3389/fmars.2021.751840

Schiller, A., et al., 2018: An overview of operational oceanography. In "New Frontiers in Operational Oceanography", E. Chassignet, A. Pascual, J. Tintoré, and J. Verron, Eds., GODAE OceanView, 1-26, doi:10.17125/gov2018.ch01.

Schofield, O., Kohut, J., Aragon, D., Creed, L., Graver, J., Haldeman, C., ... & Glenn, S. (2007). Slocum gliders: Robust and ready. Journal of Field Robotics, 24(6), 473-485.

Schmidt, W., Raymond, D., Parish, D., Ashton, I. G., Miller, P. I., Campos, C. J., & Shutler, J. D. (2018). Design and operation of a low-cost and compact autonomous buoy system for use in coastal aquaculture and water quality monitoring. Aquacultural engineering, 80, 28-36.

Schmidt, J.O., Bograd, S.J., Arrizabalaga, H., Azevedo, J.L., Barbeaux, S.J., Barth, J.A., Boyer, T., Brodie, S., Cárdenas, J.J., Cross, S., Druon, J.N., Fransson, A., Hartog, J., Hazen, E.L., Hobday, A., Jacox, M., Karstensen, J., Kupschus, S., Lopez, J., Madureira, L.A.S-P., Martinelli Filho, J.E., Miloslavich, P., Santos, C.P., Scales, K., Speich, S., Sullivan, M.B., Szoboszlai, A., Tommasi, D., Wallace, D., Zador, S., Zawislak, P.A. Future Ocean Observations to Connect Climate, Fisheries and Marine Ecosystems, Front. Mar. Sci. 6:550, https://doi.org/10.3389/fmars.2019.00550, 2019.

Serafino, F., Bonamano, S., de Mendoza, F. P., & Marcelli, M. (2021). Separation of Incident and Reflected Waves by Means of a Wave Radar System. IEEE Geoscience and Remote Sensing Letters, 19, 1-5.

Shi, W., Cao, J., Zhang, Q., Li, Y., & Xu, L. (2016). Edge computing: Vision and challenges. IEEE Internet of Things Journal, 3(5), 637–646. https://doi.org/10.1109/JIOT.2016.2579198

Sloyan, B. M., Roughan, M., & Hill, K. (2018). The global ocean observing system. New Frontiers in Operational Oceanography, 75-90.

Sousa-Lima, R. S., Norris, T. F., Oswald, J. N., & Fernandes, D. P. (2013). A review and inventory of fixed autonomous recorders for passive acoustic monitoring of marine mammals. Aquatic Mammals, 39(1), 23-53.

Sun Dan, Bin Xie, Jiahao Li, Xuzhan Huang, Jiawang Chen, Fang Zhang, A low-cost microbial fuel cell based sensor for in-situ monitoring of dissolved oxygen for over half a year, Biosensors and Bioelectronics, Volume 220, 2023, 114888, ISSN 0956-5663, https://doi.org/10.1016/j.bios.2022.114888.

Tengberg, A., Hovdenes, J., Andersson, H. J., Brocandel, O., Diaz, R., Hebert, D., ... & Stangelmayer, A. (2006). Evaluation of a lifetime-based optode to measure oxygen in aquatic systems. Limnology and Oceanography: Methods, 4(2), 7–17. https://doi.org/10.4319/lom.2006.4.7

Thaler, Andrew, S. Kersey Sturdivant, Russell Y. Neches, and J. Jacob Levenson. "THE OpenCTD." Oceanography 37, no. 2 (2024): 167-173.

Trevathan, J., Schmidtke, S., Read, W., Sharp, T., & Sattar, A. (2021). An IoT General-Purpose Sensor Board for Enabling Remote Aquatic Environmental Monitoring. Internet of Things, 16, 100429.

Tyack, P. L. (2008). Implications for marine mammals of large-scale changes in the marine acoustic environment. Journal of Mammalogy, 89(3), 549-558.

https://unece.org/environmental-monitoring

Van Vranken, C., Jakoboski, J., Carroll, J.W., Cusack, C., Gorringe, P., Hirose, N., Manning, J., Martinelli, M., Penna, P., Pickering, M., Piecho-Santos, A.M., Roughan, M., de Souza, J., and Moustahfid, H. (2023). Towards a global Fishing Vessel Ocean Observing Network (FVON): state of the art and future directions. Front. Mar. Sci. 10:1176814. doi: 10.3389/fmars.2023.1176814

Vasil Simeonov (2019). Didactical Principles of Environmental Monitoring. Chem. Didact. Ecol. Metrol., 24(1-2), 99-106. doi: 10.2478/cdem-2019-0008.

Yamahara Kevan, Elizabeth A Allan, Julie Robidart, et al. A State-of-the-Art Review of Aquatic eDNA Sampling Technologies and Instrumentation: Advancements, Challenges, and Future Prospects . Authorea. April 21, 2025.
DOI: 10.22541/au.174526739.90315230/v1

Waldmann, C., Tamburri, M., Prien, R. D., and Fietzek, P. (2010). Assessment of sensor performance, Ocean Sci., 6, 235–245, https://doi.org/10.5194/os-6-235-2010,

Wall, C. C., McKenna, M., Hatch, L. T., Van Parijs, S. M., Bochenek, R., Dugan, P., ... & Thomisch, K. (2025). Big Data, Sound Science, Lasting Impact: a framework for passive acoustic monitoring. bioRxiv, 2025-04.

Wang, Z. A. (2021). Accelerating global ocean observing: Monitoring the coastal ocean through broadly accessible, low-cost sensor networks. Marine Technology Society Journal, 55(3), 82-83.

Wang, Z. A., Moustahfid, H., Mueller, A. V., Michel, A. P., Mowlem, M., Glazer, B. T., ... & Brehmer, P. (2019). Advancing observation of ocean biogeochemistry, biology, and ecosystems with cost-effective in situ sensing technologies. Frontiers in Marine Science, 6, 519.

Wang, Y. P. E., Lin, X., Adhikary, A., Grövlen, A., Sui, Y., Blankenship, Y., Bergman, J., & Razaghi, H. S. (2017). A Primer on 3GPP Narrowband Internet of Things. IEEE Communications Magazine, 55(3), 117–123. https://doi.org/10.1109/MCOM.2017.1600510CM

Willis, Z., Heslop, E., Fietzek, P., Tirpak, L., Kocak, D.M., Rayner, R., Heupel, M. (2023). Dialogues with Industry Synthesis Report (Report no. GOOS-288 / MTS-202304)

Woodworth, P.L. and Player, R. 2003. The Permanent Service for Mean Sea Level: an update to the 21st century. Journal of Coastal Research, 19, 287-295.

Zacharia, S., Srinivasan, R., Thamarai, T., Ramadass G.A. and Atmanand, M.A.: Design of an advanced Acoustic Tide Gauge for Tsunami monitoring, OCEANS 2011 IEEE - Spain, Santander, Spain, 2011, pp. 1-5, doi: 10.1109/Oceans-Spain.2011.6003408.

Zadorozhny, A. M., Doroshkin, A. A., Gorev, V. N., Melkov, A. v., Mitrokhin, A. A., Prokopyev, V. Y., & Prokopyev, Y. M. (2022). First Flight-Testing of LoRa Modulation in Satellite Radio Communications in Low-Earth Orbit. IEEE Access, 10, 100006–100023. https://doi.org/10.1109/ACCESS.2022.3207762

Zhu, Y., Fang, T., Ji, D., Li, H., Chen, J., & Ma, J. (2024). Recent advances and prospects in on-site spectrophotometric nutrient measurement in aquatic ecosystems. TrAC Trends in Analytical Chemistry, 117723.

3GPP (2022). Release 16 Description; Summary of Rel-16 Work Items (Technical Specification 21.916). Retrieved from 3GPP portal: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3493

3GPP (2023). Solutions for NR to support Non-Terrestrial Networks (NTN) (Technical Report 38.821). Retrieved from 3GPP portal: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3525