Navigating the Future IV

Position Paper 20

Extract:
Chapter 11, *An Integrated and Sustained European Ocean Observing System*, pages 134-155

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Navigating the Future IV

Position Paper **20**

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The European Marine Board gratefully acknowledges the financial support provided by the UK National Oceanography Centre (NOC) towards the cost of printing Navigating the Future IV.

Suggested reference

European Marine Board (2013). Navigating the Future IV. Position Paper 20 of the European Marine Board, Ostend, Belgium.
ISBN: 9789082093100

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An integrated and sustained European Ocean Observing System (EOOS)

Credit: IFREMER.

11.1 Introduction

The global Ocean is subject to multiple and increasing anthropogenic and natural stressors and consequently marine ecosystems are increasingly vulnerable to exceeding tipping points which may lead to irreversible change (Bundy *et al.*, 2010). But how will society be placed in the coming decades to tackle these threats and turn challenges into opportunities? The Rio Ocean declaration (16 June 2012) called for an *“integrated approach addressing the interlinked issues of oceans, climate change, and security”* and for countries to *“Establish the scientific capacity for marine environmental assessment, monitoring, and prediction, including the implementation of……the global ocean observing system”*. Routine and sustained ocean observations are crucial to further our understanding of the complex and vast oceanic environment and to supply scientific data and analyses sufficient to meet society’s needs.

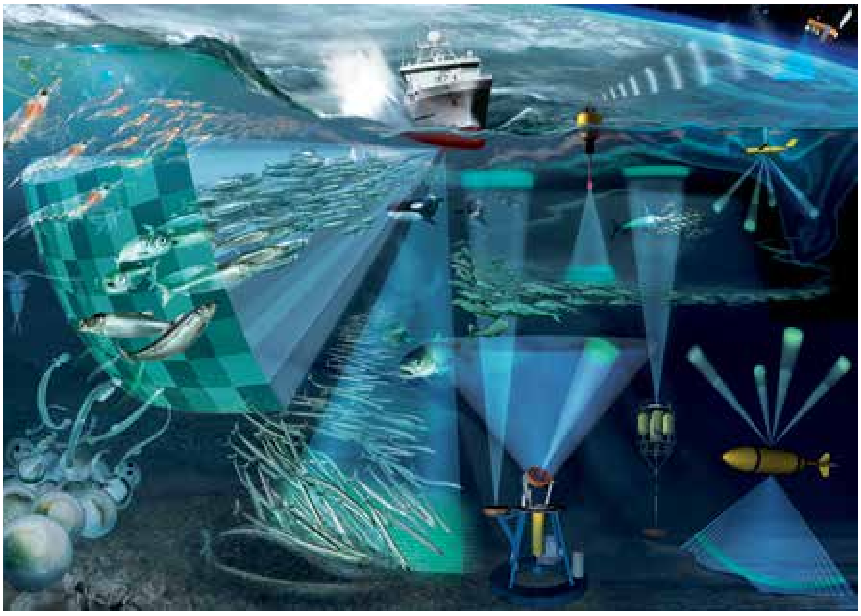
The need for such an integrated ocean observing system is particularly important in Europe because of the complexity and density of human activity in European seas and oceans. This results in a high demand for marine knowledge in the form of data, products and services to support marine and maritime activities. There is also a critical need for basic and applied marine science to inform society, ocean governance and decision-making, supporting a knowledge-based maritime economy that is sustainable into the future. A relatively mature European ocean observing infrastructure capability already exists including resources, hardware, facilities and personnel. However this is largely fragmented and the need and value for coordinated development and utilization of marine research infrastructures has been identified at a European level (MRI expert group report[1]). But how will the European Ocean Observing System (EOOS) evolve to address the needs of multiple stakeholders into the future and what are the research needs and challenges relevant to the development of such a system?

This Navigating the Future IV chapter addresses research frontiers for next generation ocean observation and current and future infrastructure developments, and places these in the context of European needs and policy frameworks. A concept for an EOOS is presented with scientific, technological, social and economic drivers and feedbacks. It is proposed that a ‘step change’ in coordination is required across the marine and maritime stakeholder community to capitalize on common requirements and promote cost-effective multi-use observation infrastructure. This can be achieved through the formation of beneficial partnerships across marine and maritime sectors and geographical regions. In addition, new models of governance and funding are discussed that could support the sustainable operation of ocean observing systems. This is vital to secure the delivery of key environmental datasets, products and services of benefit to society. A truly integrated EOOS would empower European nations to take control of assessing marine environmental status, predicting future scenarios and making informed decisions about ocean governance that balances economic growth with environmental protection. This would ultimately lead to new opportunities in many marine and maritime sectors. Such a system would also progress Europe’s position as a worldwide science and technology leader and further establish Europe’s contribution to global initiatives such as the Global Earth Observation System of Systems (GEOSS), through initiatives such as EuroGOOS and Copernicus (formerly Global Monitoring for Environment and Security (GMES)).

[1] Towards European Integrated Ocean Observation (http://ec.europa.eu/research/infrastructures/pdf/toward-european-intagrated-ocean-observation-b5_allbrochure_web.pdf)

11.2 Research frontiers driving next generation ocean observation

A variety of *in situ* and remote platforms enable ocean observations at multiple temporal and spatial scales, thus increasing the flexibility of the observation system.



Credit: Olav Rune Godø, Institute of Marine Research, Bergen, Norway.

Scientific discovery and understanding of the oceans has paved the way for human activities in the marine environment. Significant progress in international ocean observation has been made over the past decade (Busalacchi, 2010) and ocean observatories now produce crucial datasets to further our knowledge on oceanic processes including, for example, heat content, ecosystem and carbon dynamics, air-sea interaction, ocean acidification, and ocean floor substrate-fluid processes. In addition, combined *in situ* and remote sensing techniques such as ocean colour radiometry (OCR) have revolutionized our understanding of surface ocean processes and our ability to characterize global marine pelagic ecosystems and habitats (Yoder *et al.*, 2010). As the demand for marine geospatial information grows, basic science through sustained observation will continue to serve an important purpose, pushing the boundaries of our knowledge of the temporal and spatial variability of the marine environment and driving new research frontiers leading to innovation and socio-economic benefits.

Identifying science priorities, critical parameters and geographical regions to observe now and into the future is the first step towards an Ocean Observing System that will serve societal needs and advance scientific capacity. Various studies and initiatives have systematically identified research drivers and needs across the physical, geological, biogeochemical and biological oceanographic sciences that can be addressed by ocean observation (e.g. Ruhl *et al.*, 2011; OceanObs'09 Plenary and Community papers; MRI expert group final report; GEO Work Plan 2012-2015). The Global Ocean Observing system (GOOS) has also played a part in assessing the current status of ocean observations and linking research priorities with societal needs (see also the US NRC Report on Critical Infrastructure for Ocean Research and Societal Needs in 2030). The following section does not attempt to provide a comprehensive list of research priorities, but highlights some identified areas and gaps that may drive the design and operation of next generation ocean observation.

11.2.1 Temporal and spatial variability

Marine ecosystem dynamics are inherently non-linear and resolving temporal and spatial variability in the oceans remains notoriously difficult. Interpretation of ocean processes is often further hindered by a lack of multidisciplinary oceanographic time-series datasets at high enough resolution or from specific locations of interest. The non-linearity means that perceived trends in ecosystem indicators can be short-lived and variables often display a delayed response time to pressures and larger-scale climate drivers. Indeed, studies have shown that statistically robust trend analysis requires long-term time-series datasets and that a high variance of ecological indicators can reduce the statistical power for detecting trends in series of less than 10 years (Blanchard *et al.*, 2010). In turn, studies have shown that for remotely sensed data, 40 years of ocean observations are required to separate natural modes of climate variability from longer-term trends of a changing climate and ocean (Henson *et al.*, 2010).

Next generation ocean observation can build on existing infrastructure to develop multi-platform networks combining space and *in situ* ocean observation data. Each new combined data acquisition system should be designed according to a very precise scientific objective (e.g. sensor resolution, deployment strategy, acquisition frequency and duration). This will enable short-term and episodic events to be not only captured, but tracked, and longer-term change to be monitored. For example, it could facilitate a new level of understanding of ocean energetics and related biological activity at the meso-scale e.g. eddies which are focused within spatial scales of tens to hundreds of kilometres (Godø *et al.*, 2012). Understanding the effects of climatic phenomena such as the North Atlantic Oscillation (NAO) on marine ecosystems and biogeochemical cycles is also crucial if global ocean dynamics are to be understood.

11.2.2 Integrated coastal to open ocean monitoring

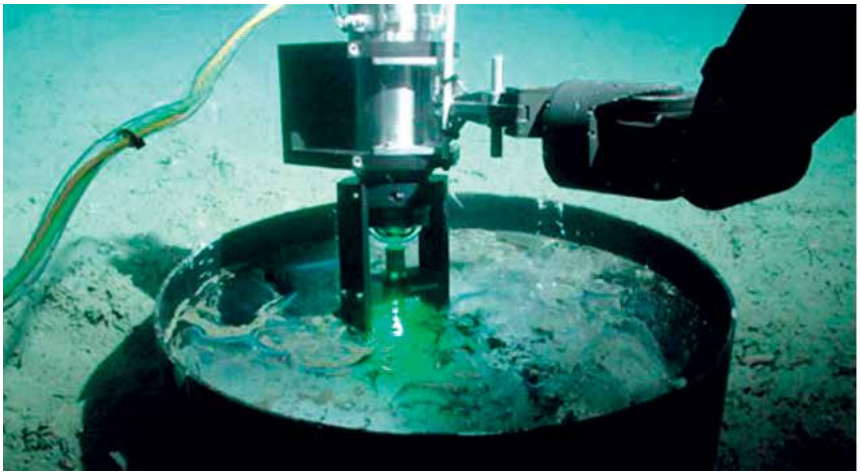
A real challenge for an integrated EOOS is to create integrated coastal to open ocean monitoring systems that will revolutionize observing and modelling of basin-scale change, allowing gradients to be assessed across major biomes (e.g., equatorial upwelling bands, sub-polar gyres). Identifying and monitoring a common set of key variables is essential to achieve this. However, the added complexity of coastal waters requires a targeted monitoring of additional variables to take account of the higher concentration of human activity in these regions. Combining advanced observation techniques is also presently under-utilized. For example, the use of satellite sensors for surface observations, and vessel-based acoustic sensors for characterizing the open ocean interior, can permit a renewed understanding of mesoscale phenomena and ecological responses caused by their physical forcing.

11.2.3 Rates and Fluxes

Whilst many key oceanic variables can now be monitored autonomously, the next level of complexity, rates and fluxes, remains less well constrained. Advancements in monitoring fluxes in real-time (e.g. ocean-atmosphere gas exchanges) and fluxes of particulate inorganic and organic carbon will significantly further our understanding of fundamental oceanic processes including atmosphere-land-ocean interactions, elemental cycling and connections with larger climate indices such as the North Atlantic Oscillation (NAO). As ocean instrumentation systems (e.g. sensors, platforms, data transmission) become more advanced and reliable, a future observing system will routinely monitor deeper into the interior of the oceans than ever before. This may profoundly change our current understanding of heat storage, boundary layers and ecosystem functioning of under-sampled areas including, for example, the mid-water meso-pelagic zone and the deep-sea.

11.2.4 A new era in biological observations

The past decade has seen a major effort towards developing marine observations targeted at a better understanding of biogeochemical cycling and ecosystem services. The international Census of Marine Life consolidated a global effort to address marine biodiversity observations (Ausubel *et al.*, 2010). Projects such as the Continuous Plankton Recorder (SAHFOS)[2] have provided unique biological datasets on the ecology and biogeography of plankton since 1931. Marine research stations have also been crucial to provide access to a comprehensive set of coastal ecosystems and state-of-the-art experimental facilities for marine research (see Chapter 2, the FP7 ASSEMBLE research infrastructure initiative[3] and the European Marine Biological Resources Centre EMBRC [4]). In addition, the capacity for autonomous monitoring of increasingly complex biological variables is improving such as using *in situ* laser spectrometry to determine the composition and chemical bonding of solids, liquids and gases within marine sediments and overlying water. Despite these achievements, a need has been identified at European level to further develop automated biological observations to characterize ecosystem health and pressures on marine biodiversity. Furthermore, present observation systems suffer from their inability to observe basic ecosystem processes at the scales of time and space in



Credit: MBARI, 2005

MBARI's deep-sea laser Raman spectrometer being used to study a tubeworm colony, about 2,300 meters below the surface of Monterey Bay. The laser Raman spectrometer can determine the composition and chemical bonding within many solids, liquids, and gases.

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[2] http://www.sahfos.ac.uk/

[3] http://www.assemblemarine.org/

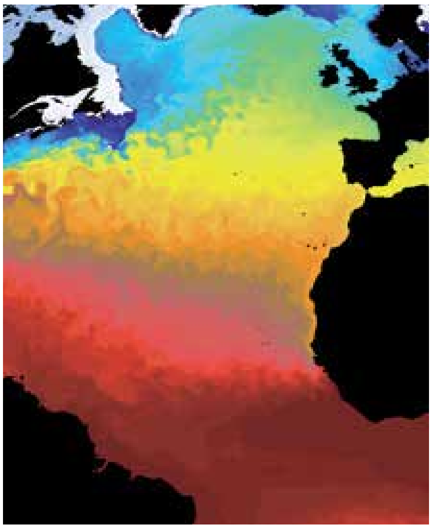
[4] http://www.embrc.eu/

which they occur, e.g. plankton net sample volumes are generally much larger than those representing life bearing processes of individuals and patches. The next decade is expected to produce technological advancements building on existing capabilities including *in situ* sensors and samplers for DNA barcoding, -omics studies and new platforms with acoustic and satellite tracking techniques (see Chapter 10 on Blue Technologies for further information).

For enhanced spatio-temporal sampling, novel acoustic and optic sampling techniques will inform about key processes from the mm to 10s of km scales and thus strengthen our ability to quantify basic ecosystem processes. Using acoustics over an extended frequency band will not only enhance spatial resolution but also enable better characterization of *in situ* the recorded biological components (biodiversity). This will support research on the understanding of ecosystem functioning and biodiversity through high resolution, long-term time-series observations (see MRI expert group report recommendations). However, this will also raise a number of important issues. As technological breakthroughs begin to offer the reality of routine, automated biological observation, a key question will be how much detail is required to monitor marine biodiversity and what are the “sentinel” species or taxa that should be monitored (O’Dor *et al.*, 2010)? In addition, as the infrastructures for biological observation grow, how will these be coordinated into an integrated and sustained system (Heip and McDonough, 2012)? An observation infrastructure initiative like the European Marine Biodiversity Observatory System (EMBOS) aims to implement a network of observation stations with an optimized and standardized methodology. These will contribute to global initiatives such as the Group on Earth Observation Biodiversity Observing Network (GEO BON) and, in particular, the Panel for Observations of Coastal and Ocean Biology and Ecosystems, which will coordinate such efforts and contribute to the Group on Earth Observation (GEO).

11.2.5 Marine Modelling

Models are a key research tool for ocean observation, providing insight into the past, present and future. Service providers such as the Marine Core Service of the European Copernicus[5] initiative now routinely utilize ocean datasets for retrospective analysis and to develop predictions of future scenarios for stakeholder use and to aid decision-making. However, models are almost always data limited, requiring observational data for model development (e.g. choosing parameterizations and parameter values), forcing, data assimilation and data-based evaluation (e.g. validation) (Doney, 1999). In addition, a key challenge for modelling is to retain essential information without being overloaded with unnecessary detail (Levin, 1992). Interaction between modelling and observation methods also needs to be strengthened so that models are integrated from coast to open ocean and developed to take advantage of emerging datasets. The availability of real-time multidisciplinary ocean datasets will be critical for the next generation of ocean models, including multi-scale coupled and nested models for producing inter-disciplinary predictions of complex environments, for example coastal marine hazard tracking.


Credit: Marine System Modelling NOC

Simulated Sea Surface Temperature (SST) and sea-ice cover from a global 1/12th degree ocean model

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[5] Copernicus, the European Earth Observing Programme (http://copernicus.eu/)

11.2.6 Risk mitigation against geo-hazards

Ocean observation measurements are essential to understand, monitor and inform mitigation against geo-hazards such as gas-hydrate stability, submarine landslides, seismic activity and fluid flow along the seabed. Seismic activity and seafloor slippages, in particular, can have direct impacts on human activities and wellbeing, such as causing damage to offshore industry infrastructure and catastrophic impacts on citizens through the formation of earthquakes and tsunamis. In order to produce robust forecasting, measurements need to be carried out continuously over sufficiently long periods of time to be able to differentiate between episodic events and trends or shorter period variations.

11.2.7 The importance of long-term ocean drilling

The Earth is a dynamic, continuously changing system. These changes occur at different time scales, from the slow building of the ocean crust and ocean basin formation, through climate fluctuations to sudden, dramatic events such as earthquakes, slope failure and volcanic eruptions and associated tsunamis. The answers to many questions regarding Earth-system processes are found beneath the seafloor. The archives of past environments and climates are recorded in sediment layers that have slowly accumulated on the seabed. Reconstructions of dramatically different past climates challenge the modelling community to improve the physics and chemistry represented in numerical climate simulations.

Credit: A. Gerdes, IODP

Core splitting onboard an International Ocean Drilling Project research cruise.

Many of the most devastating natural events are triggered underwater. To better understand the processes that cause sudden events, long-term monitoring of active areas is required. The recent events in the Indian Ocean in 2004, and in Japan in 2011, stress the urgency for progress in deciphering the triggering mechanisms and in facilitating early prediction. The development of borehole instrumentation linked with seafloor observatories provides the potential to monitor active processes in earthquake zones in real time and understand, in particular, the relationships between fluid circulation and stress release.

The Greatship Manisha, drillship IODP Baltic Sea Paleoceanography Expedition

Credit: Geoequip Marine, Island Drilling Singapore Pte. Ltd.

The only way to access the sub-seafloor environment is by drilling to collect samples. Ocean drilling also provides the opportunity for *in situ* measurements and long-term monitoring. Initiated in the USA in the late 1960s, scientific ocean drilling rapidly became an international venture, which led to the current Integrated Ocean Drilling Program (IODP)[6] established in 2003. Sixteen European countries (and Canada) participate in IODP as part of the European Consortium on Ocean Research Drilling (ECORD)[7]. The most recent phase of the IODP program concludes in 2013.

With the new 2013-2023 International Ocean Discovery Program set to get underway, it is essential to maintain the successful global approach that has been established by the IODP participant core group, consisting of the US, Europe and Japan. Scientific ocean drilling must continue with the collection of cores from key areas of interest and the deployment of instruments and technologies to achieve the measurements of parameters that are essential in understanding, and possibly predicting, unknown biosphere frontiers, climate and ocean change, and natural hazards. Some of the key future challenges and goals include further drilling expeditions in the Arctic, the Antarctic and the Mediterranean.

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[6] http://www.iodp.org/

[7] http://www.ecord.org

11.2.8 Integrated observations for evidence-based ocean governance

Marine environmental datasets are vital to support the maritime economy including marine and coastal safety, marine resources, shipping and tourism. Marine knowledge also underpins coastal and marine governance supporting a knowledge-based society. However, in a rapidly changing Earth System and dynamic human socio-economic landscape, datasets solely from the natural sciences are no longer sufficient to make informed decisions in support of Ecosystem Based Management. Close integration with the social sciences is key to delivering solutions to current and future challenges from mitigating climate change to discovering novel resources and meeting energy needs. There is particularly high demand for such datasets in the European coastal zone; an area of intense human activity that is also subject to National and European legislation. Multidisciplinary real-time ocean data support marine and coastal safety and operations and underpin weather and climate forecasting leading to enhanced understanding of ocean-climate interactions and the impacts of climate change.

Empirical data from the oceans must be interpreted alongside societal indicators to allow observations of environmental status and change to be linked to social and economic drivers and trends. Indicators of change are a powerful way to address this, offering a means to translate empirical natural science datasets into ecological indicators to assess pressure-state relationships, exploitation impacts and trends for informed marine management and policy. However, for the indicators to be effective, they must be based on a robust and sustained environmental observing programme designed to tackle issues of ocean variability. Fifty GCOS “Essential Climate Variables” (2010) have already been identified, allowing a systematic observation of the global climate to support the work of the UNFCCC and the IPCC. The concept of EOVs (Essential Ocean Variables) was recently introduced as an approach to build a Framework for Ocean Observing (see UNESCO 2012 report “A framework for ocean observing”). These EOVs are set to provide a valuable way to enhance communication and understanding across disciplines and for policy makers to have a clearer picture of changes and trends across the ocean-earth-climate system.

Clear mechanisms, such as coordination through the Scientific Committee on Oceanic Research (SCOR), will be required for defining EOVs, particularly in light of the considerable technological advances in autonomous measurement of some key biological parameters. Such environmental indicators can then be linked with socio-economic marine indicators such as those proposed by the World Bank in its ‘Little Green Data Book’ initiative. International declarations (e.g. the 2012 Rio Ocean declaration) and European legislation (e.g. the Marine Strategy Framework Directive) indicate that the demand for marine environmental assessment, monitoring, and prediction will continue to grow. Next generation ocean observation should, therefore, continue to provide new scientific knowledge and better advice for evidence-based policy assessments such as environmental status and development and management of Marine Protected Areas.

11.2.9 Geographical gaps and priority areas

The vast majority of ocean observation research and operations (with the exception of remote sensing) are focused in coastal regions and associated with the EEZs of various nations (O'Dor *et al.,* 2010). Future coordination will be facilitated through the GOOS coastal implementation plan. However, much of the open ocean, seafloor and subseafloor remains under-sampled. Observing offshore regions is highly important, not only because little is known of this vast environment, but because such open ocean systems drive many global oceanic and climate processes. In addition, these areas are likely to be increasingly exploited as commercial activities move further offshore. This includes, for example, biologically sensitive but resource rich regions such as the deep seafloor, sub-seafloor and hotspot areas of biological endemism. Ocean observation of ultra-deep water, the deep seafloor and sub-seafloor will also be crucial to identify and effectively manage ecologically significant regions as industry moves towards exploiting marine biological and mineral resources from these remote environments (Weaver and Johnson, 2012; see also Chapter 8 on the deep sea).

The high latitudes have also been under-sampled historically (Busalacchi, 2010), although monitoring of polar regions is becoming an international priority because of their recognized high climate sensitivity and the growing demand to exploit the increasing areas of international open waters resulting from Arctic summer sea-ice retreat. Scientific research through ocean observation will be crucial to provide data for understanding the rapid changes in this dynamic system, validate and constrain model predictions, and underpin informed decision making and future international agreements for polar maritime navigation and marine resource exploitation (e.g. commercial fishing, oil/gas exploration). Again, coordination between countries and across sectors will be essential to achieve the scale of observations necessary to provide a thorough baseline knowledge of the Arctic ecosystem before commercial exploitation takes off (Haugan, 2013).

11.2.10 Future ocean trends

The global ocean is a dynamic system and the science priorities and key variables of tomorrow are likely to be different or even include currently unknown phenomena. Natural science and a future ocean observing system should be adaptable and resilient to known and unknown future trends e.g. ocean warming, enhanced stratification and increase in mid-water oxygen minimum zones. Each of these trends would, in turn, influence the biogeochemical signatures of oceanic regions with implications for ocean productivity, nutrient cycling, carbon cycling, and ecosystem functioning. Across European closed and semi-enclosed seas (e.g. the Baltic, Mediterranean and Black Seas) these changes will potentially have a profound impact on marine and maritime sectors such as tourism and aquaculture.

11.3 Building on the existing ocean observation capability

Albex Lander used for seafloor observation

Infrastructure is the foundation for an ocean observing system, providing the platforms and services to deliver environmental data, information and knowledge. Essential components include both the hardware and core resources including people, institutions, data and e-infrastructures that maintain and sustain operations. A relatively mature ocean observing capability already exists across Europe. This can be split into four infrastructure fields (as identified by the EU FP6 MarinERA project), namely (i) research fleets; (ii) observing and monitoring systems; (iii) land-based infrastructures e.g. marine stations; and (iv) data management. The ocean observing and monitoring systems include established networks of space-based, airborne, and *in situ* platforms and sensors, e-infrastructure components for data management, and the computing power necessary for maintaining these systems and delivering data, products and services. Such infrastructures are maintained by experienced operators including technical experts, engineers and scientists that are crucial for the maintenance and sustainability of the system. The section below provides information on the current state-of-the-art of European ocean observing infrastructure. A more detailed European MRI inventory and mapping has been prepared by the SEAS-ERA project[8] and the final report of the EC MRI expert group.

11.3.1 *In situ* observation

Methods for ocean observation are constantly evolving and innovation is an essential driver for science and engineering excellence and technological advancement. New smart sensors, techniques and platforms are emerging to provide automated solutions to multidisciplinary marine monitoring. In terms of *in situ* ocean observation, improvements to sensitivity, accuracy, stability, resistance to oceanic conditions and depth rating are all key to ensuring high quality, sustained data. An increased interest and effort in ocean observation in the 1990's led to a huge technological advancement in automated sensors for monitoring physical variables such as temperature, salinity and currents. Today, thanks to global projects such as ARGO[9] and OceanSITES[10] and European initiatives including EuroSITES[11], JERICO[12], EMSO[13] and Esonet[14], such variables are monitored and provide datasets which underpin the operational Global Ocean Observing System (GOOS[15]).

Over the past decade, there has been a drive to advance biogeochemical and biological sensors and samplers (Gunn *et al.,* 2010). As a result, novel sensors for the autonomous measurement of variables from nitrate to methane and from micronutrients (e.g. iron and manganese) to alkalinity, are emerging. Accurate and high precision sensors for such variables are urgently needed to contribute to an operational GOOS. A similar technological leap is now required to enable routine autonomous *in situ* biological and chemical measurements of marine biodiversity (e.g. molecular methods using genomics). Much work is focused on minimizing power requirements and reducing the size of sensors towards miniaturized lab-on-a-chip micro sensors to minimize the pay load and enable multi-parametric observation from single platforms such as gliders and drifting buoys. Micro sensors can also be fitted to marine organisms (e.g. seals or small whales) which act as biological observatories, often producing vital profile information (Boehme *et al.,* 2010).

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[8] www.seas-era.eu/np4/19.html

[9] www.argo.net

[10] www.oceansites.org

[11] www.eurosites.info

[12] www.jerico-fp7.eu

[13] www.emso-eu.org

[14] www.esonet-noe.org

[15] www.ioc-goos.org

Credit: HCMR

Ocean buoy and mooring for fixed-point measurements

Operational robustness and automation of advanced scientific equipment (e.g. Ferrybox) allow data to be collected by the commercial fleet thus expanding observations in time and space to an extent that would otherwise not be possible. Utilization of these opportunities is still in its infancy and will be important for large and power-hungry systems (e.g. acoustics) that cannot yet be deployed on autonomous platforms. However, whereas the space component of the European ocean observing system is managed and developed by the European Space Agency, the Copernicus (GMES), the *in-situ* component is not yet coordinated by one overarching structure but is sustained by the numerous stakeholders, which often leads to duplication.

Credit: Ambra Milani, Sensors Group, NOC, Southampton and SENSEnet, Marie Curie Initial Training Network (ITN).

Iron and manganese sensor in insulating case, attached to CTD-Pump carousel, ready for deployment in the Baltic Sea (IOW, Warnemunde, Germany).

Credit: David White, National Marine Facilities, NOC, UK

Autosub-3 being recovered from the Black Sea in 2010 onto the Turkish research vessel "Piri Reis" as part of a scientific study led by Leeds University, UK, looking at the flow in the deep saline channel from the Bosphorus to the Black Sea in May 2010

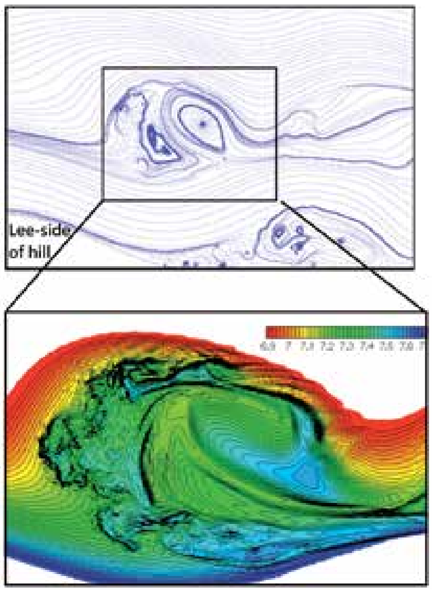
11.3.2 Sentinel satellites

The space component of ocean observation includes sentinel satellites in support of ocean forecasting systems, and for environmental and climate monitoring (see EC COM(2012) 218 final). Progress in space-borne sensors and algorithms for satellite ocean colour radiometry (OCR) missions will expand the scientific and societal applications of ocean remote sensing. Monitoring of optically complex coastal regions should be greatly enhanced by multiple spectral bands providing more detailed information on the constituents of suspended particulate and dissolved matter. Current capabilities for monitoring polar regions will be improved by increasing the quality of moderate resolution polar orbiting observations (Yoder *et al.,* 2010). In addition, the ability to calculate indices of ecosystem structure, including phytoplankton cell size, would add significant value to current capabilities for studying marine ecosystems from space (Kostadinov *et al.,* 2009).

11.3.3 Oceanographic information in the new data age

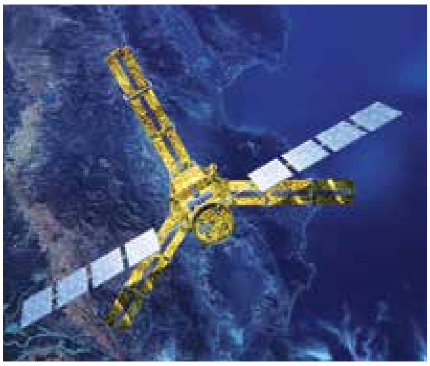
Next generation ocean observation will enable rapid and wide distribution of information (data, methods and products) (Busalacchi, 2010). However, real-time delivery of large, multivariate data sets, with increasing temporal and spatial resolution, will demand a new approach to data stewardship from storage and open access, to integration and standardization. The field of Information and communication technologies (ICT) will be an increasingly crucial component of the marine data management infrastructure. Future observing systems will need to be adaptable to new ICT approaches in order to embrace the exponential growth in multivariate data and the ongoing progression towards interoperable systems using agreed standards (e.g SeaDataNet). In particular, this will lead to the requirement for a new bio-physical data framework to allow complex biogeochemical and biological datasets and their metadata components to be available alongside climatic and physical oceanographic datasets (Vanden Berghe *et al.,* 2010).

High performance computing facilities and e-infrastructure, including cloud computing and internet-enabled 'smart' infrastructures, may revolutionize data storage, accessibility and integration. This in turn is driving new innovations and capabilities in environmental modelling. For example, the UK National Supercomputing Service, HECTOR, is a high-performance computing facility that has greatly enhanced the capacity to study ocean turbulence, utilizing a billion grid points to conduct Direct Numerical Simulations (DNS) of entire wind flows (Yakovenko et al., submitted). A major challenge is the development of new methods for analysis of these complex spatio-temporal data types that yield information not just about the ocean state, but also the underlying dynamical processes. Model data fusion (or data assimilation) algorithms provide an attractive approach to exploit these new data streams within a robust statistical framework and to explore optimal use of observing capabilities to achieve monitoring, assessment or forecasting goals.



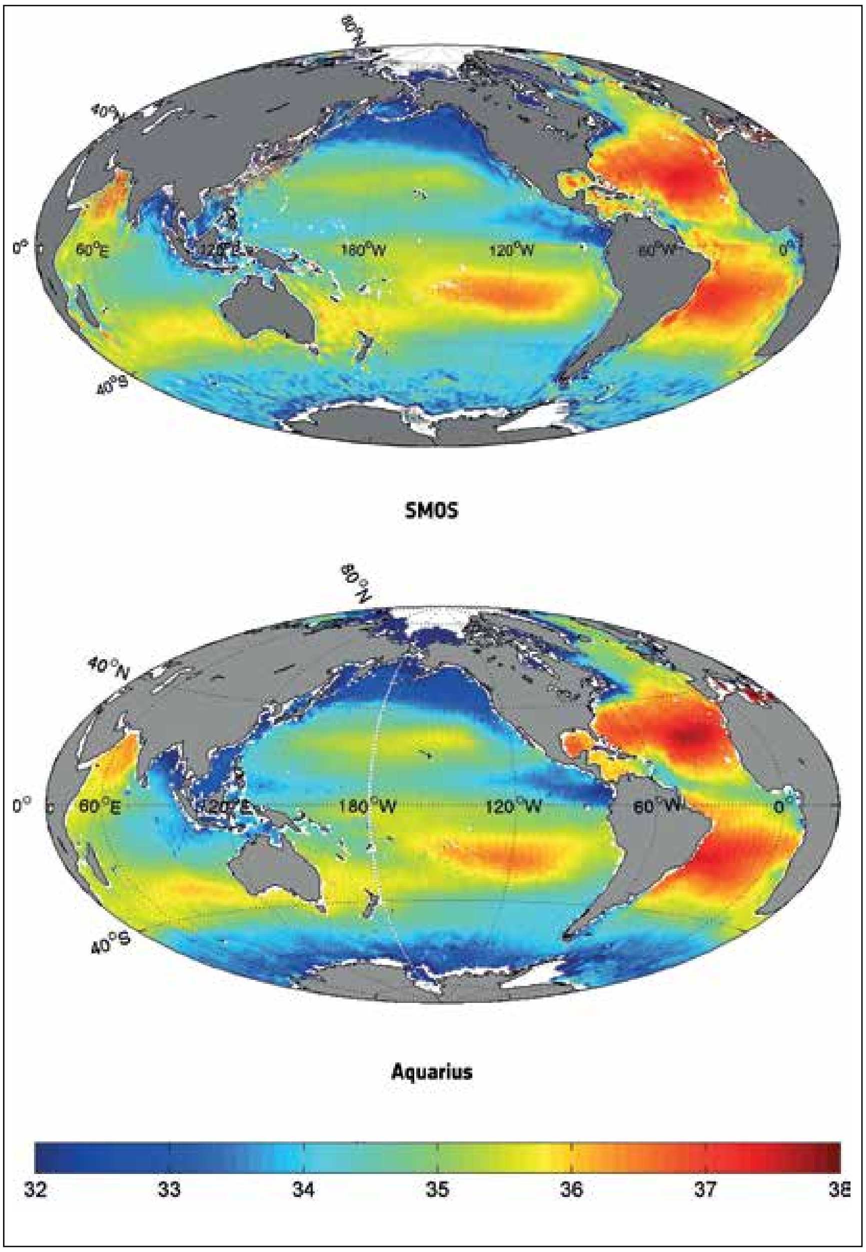
Credit: EPCC, University of Edinburgh. HECTOR project, UK

Visualisations of a Direct Numerical Simulation (DNS) of an entire wind flow on ocean turbulence investigation



Credit: ESA - P. Carril

↑The Soil Moisture and Ocean Salinity (SMOS) Earth Explorer satellite



→Global salinity maps from the European Space Agency's Soil Moisture and Ocean Salinity (top) and Aquarius (bottom). satellites. SMOS and Aquarius are complementary by way of their spatial and temporal coverage and their viewing angles. By combining their data, maps of ocean salinity will be even more accurate and robust.

Credit: IFREMER/ESR/ESA/NASA)

11.3.4 Intelligent infrastructure

The growing application of "intelligent sampling" is transforming event-driven scientific research and marine management, offering the chance to interact with autonomous sensors in near real-time and to change the sampling time, resolution, depth profile or trajectory of the platform. Some extra assets are required to allow for redundancy in the system. This is important for two reasons. Firstly redundancy allows strategic planning in the event of failure of equipment or technology before scheduled maintenance or in the case of a surge. Secondly, having a common European pool of assets allows equipment to be used as a rapid response mechanism to ensure that re-directed or additional monitoring could take place in case of an episodic event or environmental disaster such as an oil spill, earthquake or tsunami. In addition, science and technology are continuously evolving and an effective and relevant ocean observing system needs some level of adaptability to respond to new breakthroughs and insights permitted by new knowledge (see GEO 2012-2015 Work Plan).

11.3.5 European context and policy frameworks

Ocean observation is a key component to the EU Strategy for Marine and Maritime Research, providing marine environmental datasets as a solid science base to support delivery of the societal needs specified in the Integrated Maritime Policy (IMP). In the past decade, with the success of global projects such as Argo (and its European contribution, EuroARGO[16]) and the launch of inter-governmental initiatives such as GEOSS (the Global Earth Observation System of Systems), ocean observation has become a higher priority on the worldwide environmental political agenda. At a European level, this has been further supported by community responses such as the EurOCEAN 2010 Ostend Declaration which stated that *"Addressing the Seas and Oceans Grand Challenge requires the development of a truly integrated and sustainable European Ocean Observing System."*

However, despite progress towards increased integration of marine infrastructures at a pan-European scale, there remains a complex landscape of ocean observation infrastructures across Europe. The Marine Knowledge 2020 initiative provides a potential unifying framework for a future European Ocean Observing System (Marine Knowledge 2020; EC COM(2012) 473 final). High investment is often required both for the hardware itself and for its ongoing maintenance and operation. The sustained funding necessary to achieve this is often difficult to secure. Such infrastructure costs are predominantly funded by Member States, although preparatory actions for pan-European marine research infrastructures, networking and integration activities are funded by the European Commission through EU research funds. A number of European initiatives have been funded to assess the current state of play of research infrastructure in the environmental and earth sciences domain (MRI expert group final report). The adoption of legal instruments such as the ERIC[17] may facilitate the Member States in enabling collaborative funding of research infrastructure projects from national budgets. This route is currently being pursued by EMSO and EUROARGO, two marine research infrastructures on the ESFRI roadmap.

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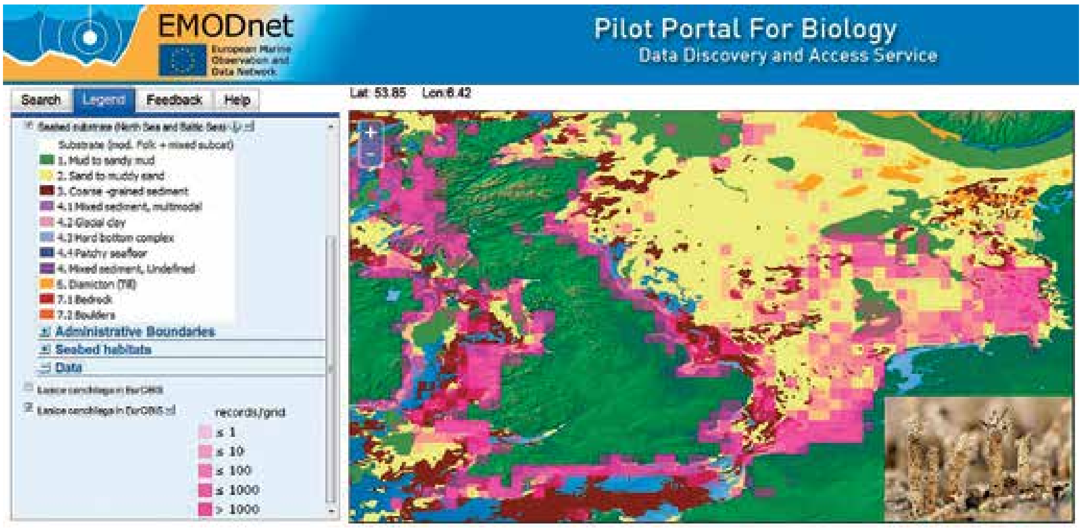
[16] http://www.euro-argo.eu/

[17] http://ec.europa.eu/research/infrastructures/index_en.cfm?pg=eric

Despite the fact that EU funds support pan-European marine data service initiatives such as Copernicus, there may be an increasing call for Member States to mobilize structural funds to support such programmes (see the “Funding MRIs” section of MRI expert group final report). As a result, it is likely that novel funding models and dynamic governance will be required to establish long-term commitments into the future (GMES Copenhagen Resolution and EC COM(2012) 218 final). Ongoing evaluation of the socio-economic and environmental contributions of marine research infrastructures is, therefore, crucial to establish the impacts (both positive and negative) of such infrastructures on employment, GDP, education and innovation (see MRI expert group final report, Annex 2 and Figures 1, 2 & 3). In addition, it is likely that legislation such as the Marine Strategy Framework Directive (MSFD) will become one of the most important policy divers for MRI development at a European scale in coming decade.

11.3.6 Geo-spatial data and information systems



Credit: European Ocean Biogeographic Data System (EurOBIS))

EMODnet Biology data portal providing a view of the southern North Sea combining an integrated broadscale seabed sediment map (1:1 million scale) and distribution data (aggregated per 15 by 15 minute grid with a temporal scope from 1977 to 2009) for the reef building Polychaete worm (*Lanice conchilega*, Pallas, 1766).

At present many ongoing observation and data networks are producing openly accessible, high quality data, services and products for society, contributing to initiatives such as SEADATANET[18], EMODnet (see Marine Board-EuroGOOS EMODnet Vision Document[19]; EMODnet Road Map[20]), the Ocean Biogeographic Information System (OBIS) (Vanden Berghe *et al.*, 2010), GMES Marine Core Services and international initiatives such as GEOSS. These initiatives utilize ocean datasets to provide societal products including ocean analyses and forecasts for applications ranging from maritime safety to climate monitoring. However, there is a real need for such initiatives to become more operational and to interlink the full data pathway from observation to analysis and product/service. At present, shortages or gaps in national commitments are still resulting in gaps to crucial datasets that feed into downstream services. The requirements of both space and *in situ* ocean observation systems should, therefore, be evaluated to ensure that a future ocean observing system can deliver uninterrupted data streams and can react to new priority areas as science and societal needs change.

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[18] www.seadatanet.org

[19] http://www.marineboard.eu/images/publications/EMODNET-7.pdf

[20] EMODNet Roadmap https://webgate.ec.europa.eu/maritimeforum/system/files/roadmap_emodnet_en_0.pdf

In recent years there has been a growing need to assess the costs and benefits of key ocean observing infrastructure components (e.g. see FP7 project SEAS-ERA Deliverables 2.2. and 2.4 and FP7 GISC project final deliverables). These would now benefit from a strategic overview aided by observing system simulation experiments and data assimilation in models to assess the added value and complementarities of all assets (space and *in situ*) to ensure that the most cost-effective system is in place and that data management and service initiatives receive the optimum datasets in a timely manner. The enormous data stream from the envisioned observing system will also require a periodic and systematic prioritization to ensure that the optimum infrastructure is in place as scientific and societal demands for certain essential datasets change. Regional monitoring systems in the context of EuroGOOS, and initiatives such as BONUS and regional agreements have taken a basin-scale approach to interface science and governance. There is a real need for member states and third countries to share a collective responsibility for the delivery of healthy seas. However, reconciling these different viewpoints towards an integrated approach whilst maintaining member state commitments is vital to ensure a balance between environmental health and socio-economic viability and the importance of societal values in evaluating stakeholder perspectives and trade-offs (Ounanian *et al.,* 2012).

11.4 Towards an integrated, efficient and sustained ocean observing system

A Concept for a European Ocean Observing System

It is strategically important that a truly end-to-end European Ocean Observing System (EOOS) is developed to provide the environmental data essential for the next generation of ocean science and a sustainable maritime economy. The EOOS should be smart, resilient and adaptable, with constant feedbacks to enable each stage to inform, drive and deliver high quality, relevant and timely environmental products and services for society (see Figure 11.1). This circular, inter-dependent system, is comprised of four pillars namely stakeholders, infrastructure, data services and outputs (products and services). These four pillars are all crucial to provide relevant and timely products for society in areas including stewardship of the marine environment, understanding the ocean and climate and supporting the marine economy and maritime safety (see MRI expert group report; Section IV). The system should be inherently open to adaptation and innovation, ensuring enhancements can be made to each component that promote innovation, growth and knowledge across the whole system, e.g. to the observation network or to the harmonization of data management protocols and data portals.

A future European Ocean Observing System (EOOS) should build on the wealth of existing infrastructure capabilities and multi-platform assets already in use across European marine waters, further integrating infrastructures, institutions, resources and information to deliver societal benefits (see GEO WP2012-2015 Work Plan). There is, therefore, an ongoing need for evaluating observation networks to identify gaps and priorities, as highlighted in the Green Paper on “Marine Knowledge 2020: from seabed mapping to ocean forecasting” (Marine Knowledge 2020 COM (2012) 473 final).

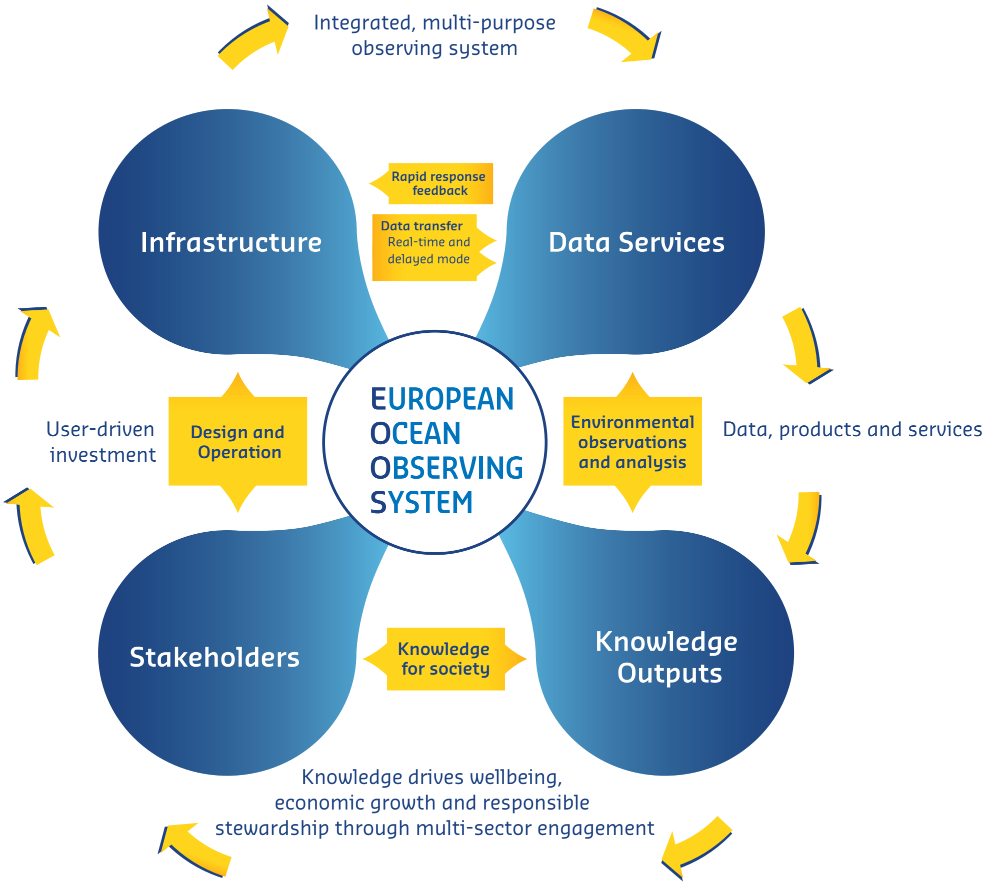

Figure 11.1

Conceptual diagram of the European Ocean Observing System showing its key components (stakeholders, infrastructure, data services, knowledge outputs), drivers, inter-dependencies and applications (a more detailed breakdown of each component is provided in the table below). A future integrated EOOS should form the European contribution to the Global Ocean Observing System and to the European marine component of the Global Earth Observation System of Systems.

Credit: K. Larkin, European Marine Board Secretariat

TABLE 11.1 Components of the European Ocean Observing System

EOOS Infrastructure	EOOS Data Services
Integrated remote and *in situ* hardware providing a multi-purpose observing system, including: • Platforms (e.g. ships, satellites, moorings) • Computing and modeling facilities • Resources (e.g. technical, scientific and administrative personnel) are also vital to support sustained core operations	Complimentary data management centres, online portals and repositories providing open access to data, observations and knowledge for EOOS Stakeholders. • Real-time / operational services including forecasting, maritime safety and security • Delayed mode including non-autonomous observations
EOOS Stakeholders	**EOOS Knowledge outputs Products and services for Society**
• European citizens • Member States and funding agencies • European policy makers • Scientists (natural and social), engineers and technologists • Environmental data / IT managers • Marine and maritime industries e.g. fishing, tourism, navigation, offshore energy (oil/gas; renewable), security • Non governmental Agencies	• Environmental analyses (trends, ranges), assessments and prediction forecasts for marine and maritime policy, environmental hazards, defense and security • Fundamental and applied science driving innovation and growth • Sustainable use of the coastal and marine environment for resources (e.g. food, fuel, pharmaceuticals) tourism and recreation

Initiatives including the EMODNet data portals in combination with SeaDataNet are already implementing this by identifying and mapping existing data and observation networks. The ongoing effort to determine gaps in data and observation systems (e.g. EMODNet phase 2 'Sea-basin checkpoints') will allow further definition of additional sea basin observation and data needs to address societal challenges and EU marine and coastal policy requirements. Successful implementation of an EOOS should form the overarching umbrella for coordinating Europe's ocean observation capability. This should utilize existing networks such as EuroGOOS which plays a key role in the area of operational oceanography; a role that is likely to grow as EuroGOOS moves towards consolidation as a legal structure. A strong EOOS will also require improved coordination between research and operational platforms forming beneficial partnerships between public and private sectors and integrating at local, national and regional scales.

Multi-purpose ocean observation

Historically, the ocean observation system has developed independent components to meet the needs of the oceanographic research and operational communities. However, partnerships between the public and private sector are emerging as a relevant way to serve the needs of users (Rio Ocean declaration, 2012), increase efficiency and drive growth in employment, GDP, education and innovation (MRI expert group report). Next generation integrated infrastructure will, therefore, enable research and operational systems to be mutually supportive and beneficial (Busalacchi, 2010). In many cases, such collaborations are already in existence, combining academic research with service provision to address environmental legislation and policies, and societal needs. The growing potential for "intelligent sampling" is supporting inter-disciplinary research and beneficial partnerships between stakeholders, fostering multi-use of observing platforms. For example, in the Mediterranean, there are a number of underwater arrays of sub-surface moorings funded largely to study neutrino particles. However, in many cases, oceanographers are collaborating with particle physicists to conduct mutually beneficial interdisciplinary research, e.g. bioluminescence studies, ecosystem dynamics.

There are also examples of public-private partnerships and multi-sector investment where stakeholders are working together to produce sustained ocean observing platforms for both fundamental and applied research (e.g. SmartBay, Ireland). In Norway, fishing vessels have been designed and equipped for collecting ecosystem information, thus extending the possibilities to collect data in time and space in support of management. The petroleum industry has a unique network of cables and seabed installations that support most essential sensors for marine monitoring. The extended focus on sustainable development has made industry more interested in collaboration and there is a large potential for stimulating integration of marine monitoring instrumentation in industry-owned infrastructure.

It is clear that shared ocean infrastructure investment and maintenance (across the full life cycle of infrastructure) could ultimately reduce costs, lead to more efficient and harmonized use, surge capacity and produce new opportunities. A step-change is now required to take the current observing capacity, designed for understanding the marine environment, towards a user-driven operational ocean observing system. Long-term research drivers and needs should still be at the core of the design process, but these need to be clearly linked to social, economic and infrastructure requirements with feedback by multi-sector stakeholders to drive innovation in the system.

Fundamental science discoveries of the future may pave the way for applied research and ecosystem-based management. For example, as pressure mounts to explore and exploit potential natural resources in the polar regions and the deep-sea, there is a need for the research community to discover and identify hotspot or Ecologically and Biologically Significant Areas (EBSAs) to facilitate ecosystem based management in the future. Despite the existing capability of observing platforms covering the space, air and sea, the disparate nature of the disciplines, stakeholders, datasets and focused expertise of researchers and specialists, means that few studies are truly holistic, creating further issues for policy makers requiring synergistic summaries regarding the status of a research field. For example, the impact of ocean acidification on an entire coral reef ecosystem will have both environmental and economic consequences in terms of potentially negative impacts on tourism and coastal defence. The current lack of cross-sector communication makes it difficult to assess the full human footprint on an oceanic region and the likely trajectories for marine variables and indicators in the region based on social and economic growth models. Innovation will also be driven by cross-collaborations between scientific disciplines and domains. For example, the fields of medicine, marine biotechnology and robotics are already providing applications which can be applied to enhance ocean observation of the marine environment.

Flødevigen marine research station, Norway

Credit: Institute of Marine Research

11.5 Recommendations

In reality, the future EOOS will be a system of systems, building on existing initiatives and establishing long-term support through mixed funding models, utilizing a wide range of funding. There is a real need for cross-disciplinary research and multi-stakeholder engagement. Natural and social science questions and research topics need to be mapped against societal challenges, policy needs and economic opportunities to ensure the observing system supplies relevant products and services for society. However, the added value and benefit of an integrated system will be enormous. The simultaneous and synthetic observation of multi-variable physical, biogeochemical and biological information from space-borne and *in situ* surface, water column and seabed components will revolutionize our understanding of various oceanic processes. Through mutually beneficial partnerships and effective science-policy interfaces, such information and knowledge will empower society with the tools to monitor, understand and predict ocean processes and the tools for sustainable management of the ocean into the future.

There is a clear need to integrate and enhance the existing European ocean observing capacities to enable a fully integrated, sustained system that can deliver high quality information and knowledge to underpin environmental policy and management. To this end, a future European Ocean Observing System (EOOS) will need to further integrate marine observations from the coast to the open ocean and from the surface to deep sea, promote multi-stakeholder partnerships for funding and sharing of data, and align with global efforts within a coherent framework to engage all countries and work towards a truly integrated global ocean observing system.

Key recommendations for the future operation, funding and sustainability of EOOS include:

1. **A common vision for the EOOS**

   A common vision should be developed for a system of systems with individual ocean observation infrastructure assets contributing to a wider, strategic network. Coordination could include establishing an independent leadership council to maintain an overarching/strategic outlook of the independent funding mechanisms for EOOS and the different stakeholder interests and priorities.

2. **Promote excellence and quality**

   Scientific excellence and high quality environmental data delivery should remain a key priority so that the infrastructure design and location of observing systems can accommodate operational services in tandem with higher-risk, blue skies research. Research can, in turn, drive technology breakthroughs and allow scientific experimentation and hypothesis testing to establish ranges, thresholds and trends in marine ecosystems, helping to constrain future scenarios. There should be more emphasis on an interdisciplinary approach and the socio-economic value of the information produced to support future research priorities.

3. **Develop the EOV concept**

   The concept of Essential Ocean Variables (EOVs) should be further developed as a way of translating marine environmental data into indicators of change that can be used by policy makers and wider stakeholders in tandem with Essential Climate Variables (ECVs) for assessments of variability and trends across the ocean-Earth-climate system.

4. **Gap analysis – societal needs**

   Conduct periodic critical gap analyses through stakeholder consultation to assess the environmental and societal relevance of marine research infrastructures and identify future priorities and capabilities based on societal needs and state-of-the-art science and technology developments in all areas of infrastructure from ocean platforms to high power computing/modelling facilities.

5. **Gap analysis - modelling**

   Continue to support the use of environmental models and statistical data assimilation methods for predictive capabilities and as a tool for identifying gaps in the current observing system. Many environmental models are now at a mature, highly complex stage of development. The use of models for gap analysis is currently under-utilized and largely centered around data assimilation to produce future scenarios or retrospective reanalysis for validation.

6. **Training**

   Networking and training of scientific users will continue to be essential to define common standards of practice and to ensure Europe maintains and develops an expert pool of personnel to support the ocean observing system from infrastructure development to maintenance, data management, analysis, and delivery of goods and services.

7. **Access**

   Facilitate access to ocean infrastructure by the European and global community across stakeholder groups and sectors (engineers, natural and social scientists) providing an opportunity for international collaboration and interdisciplinary studies of oceanic systems in the context of societal drivers.

8. **Data standardization**

   Encourage the further development of a coordinated data management infrastructure (building on SEADATANET and EMODNET) so that European marine data management adopts common (or interchangeable) standards to maximize the outputs and synergies between these data centres and portals.

9. **Adaptability**

   Ensure that the ocean observing system addresses risk, factoring in a degree of redundancy for crucial time-series and developing a plan for enabling rapid and coordinated pan-European responses to monitor and understand rare/unexpected events, including environmental disasters (e.g. oil spill), natural hazards (e.g. storm surge, earthquake/tsunami, volcano) or biological phenomena (e.g. Harmful Algal Blooms).

10. Innovation in observing

Invest in research and development for the continued innovation of EOOS infrastructure. This should include funding for ocean sensors (e.g. biological, acoustics), platforms and cross-sector research to ensure marine science takes advantage of state-of-the-art developments across other sectors (electronics, energy, communication and information technology).

11. Sustainable funding mechanisms

Innovative funding mechanisms should be developed to sustain the European Ocean Observing System. Funding should be secured for the full life-cycle of ocean observation, from deployment, maintenance and operation to retirement/decommissioning or movement of assets to a new location depending on evolving science needs. It is likely that a mixed model will be the most robust funding strategy for long-term sustainability.

Funding opportunities could include:

- Mutually beneficial public-private partnerships and stakeholder investment for research infrastructures that support the development (and investment) of marine industries and other stakeholders, e.g. from the marine renewable energy and off-shore aquaculture sectors.
- European structural funds for marine research infrastructures to support innovation, sustainable development, better accessibility and regional cohesion across European ocean observation capabilities.
- European funding to support the research infrastructure networks to develop longer-term frameworks (e.g. I3 initiatives) and pan-European legal instruments (such as ERIC) that will enable coordinated Member State investments. Improved coordination of Member State investments could be achieved through JPI-Oceans.

Credit: IFREMER

Remote underwater video system on a New Caledonian reef as part of a Marine Protected Area monitoring programme

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