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Lead authors	Albert Fischer (IOC/UNESCO), Michael Ott (IOC/UNESCO)
Contributors	Erik Buch (EuroGOOS), Mark Dickey-Collas (ICES), Vicente Fernandez (EuroGOOS), Johannes Karstensen (GEOMAR), Artur Palacz (IO PAN), Isabel Sousa Pinto (CIIMAR), Maciej Telszewski (IO PAN)
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Initial AtlantOS Requirements Report

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1 Introduction

The overarching goal of AtlantOS is to deliver an advanced framework for the development of an integrated Atlantic Ocean Observing System that goes beyond the state-of–the-art, and leaves a legacy of sustainability after the life of the project. The sustainability of the observing system is intimately linked to its fitness-for-purpose, how closely it meets the requirements of society and of science for sustained ocean observations and information.

This *Initial AtlantOS Requirements Report* collects information about the societal drivers for sustained Atlantic Ocean observations, including applications and major scientific questions, the phenomena to observe, Essential Ocean Variables, and contributing observing networks, using the ideas of the *Framework for Ocean Observing* (2012) as an organizing framework.

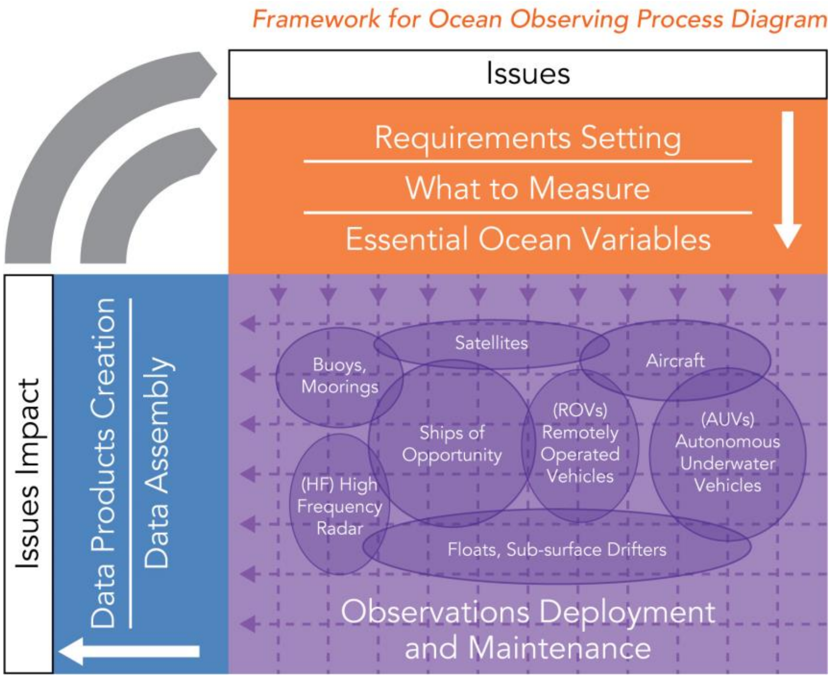


Figure 1: Processes in the *Framework for Ocean Observing,* with feedback loops in the definition of requirements and the outputs of the observing system, and a check for fitness-of-purpose of these outputs against societal drivers.

The *Framework for Ocean Observing* identifies lessons learned from the successes of existing ocean observing efforts, and provides an internationally-accepted common language and guidance for expanded collaboration in sustained ocean observations. It is focused on a systems approach:

- delivering a system based on common requirements, coordinated ocean observing elements, and common data and information streams,
- using "Essential Ocean Variables" (EOVs) as a common focus for requirements, defined based on *feasibility* and *impact* on societal and scientific drivers, and
- evaluation of "readiness levels" for each of these system components.

Identifying a common approach to requirements across the stakeholders of Atlantic sustained ocean observing systems will help develop a common understand that facilitates the joint investment needed to build and maintain an integrated AtlantOS. It also encourages integration of the observing system, ensuring that we can develop an infrastructure for both operational services and research.

Improving the *feasibility* of sustained ocean observations is an innovation and research activity that other parts of the AtlantOS project are engaging in. Innovation and improved feasibility of observation has the potential to change the equation about what is essential to observe, by being able to measure at lower cost, with new variables, or with greater accuracy. While feasibility of observations is constantly evolving, the natural system is more constant, hence a focus in requirements on EOVs that should be more time-invariant than the observing technology used to capture them. This also means that any requirements document also has a limited shelf life, and ongoing sustained evaluation processes need to accompany any sustained observing system such as AtlantOS.

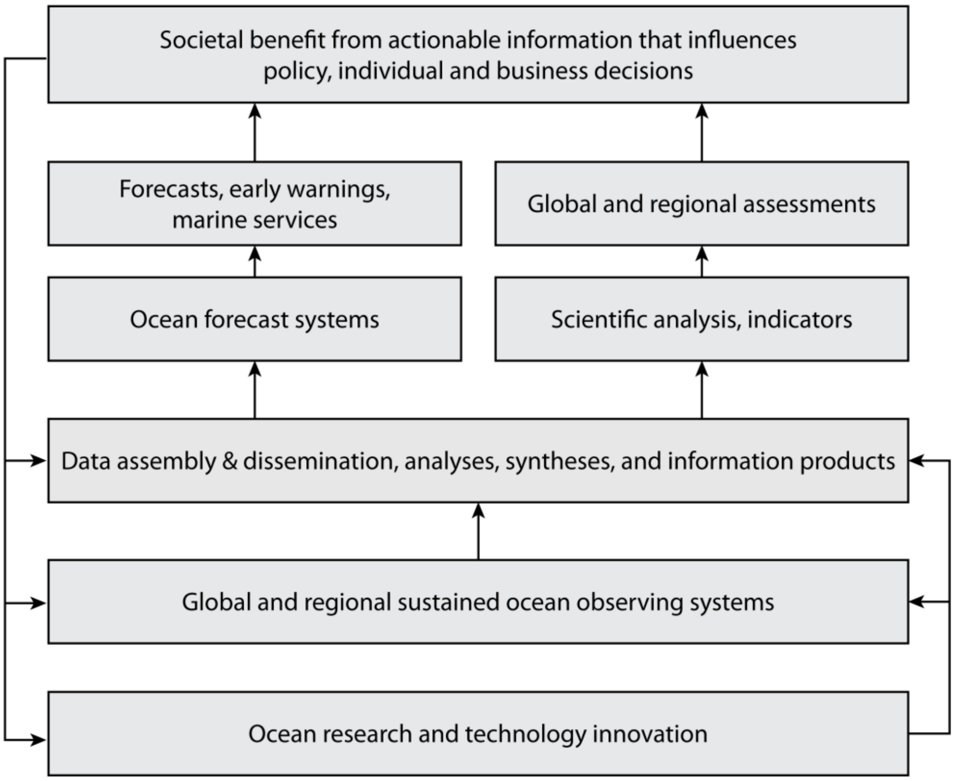


Figure 2: An illustration of the value chain linking sustained ocean observations with societal benefit. *(adapted from the G7 Ocean Expert Group think piece, May 2016)*

The *impact* of sustained ocean observations derives from a *value chain* (see Figure 2) that links:

- research and technology innovation,
- sustained observing systems,
- data management systems, analyses, syntheses, and information products,
- ocean forecast systems and scientific analysis,
- operational services and scientific assessments,
- to societal benefit.

Identifying requirements, therefore, begins with the identification of the societal benefits that can be derived from sustained ocean observations, and an understanding of the elements of the value chain that allow the derivation of these societal benefits. Sustained ocean observing systems will benefit from close alliance with ocean research and technology innovation, which has always been the source of the observing platforms and sensors that make up sustained observing systems. Data from the observing system then must flow into systematic data assembly and dissemination centers, where they can also be transformed into analyses, syntheses and information products, for use in scientific research or for direct input into indicator frameworks or ocean forecast systems. Here the value chain diverges somewhat into two paths based on our readiness to accurately model the phenomena in question: one through ocean and climate forecasting systems into forecasts, early warnings, and marine services that allow individuals and businesses to make decisions, and the second through scientific analysis or indicator frameworks to global and regional assessments and policy briefs that can inform government or business decisions and policy. This reinforces the dual purposes of AtlantOS as a sustained infrastructure for operational benefit as well as for scientific research. For operational services, AtlantOS's primary concern will be to deliver estimates of the state of the ocean, and for scientific analyses and assessments, AtlantOS's primary concern will be to provide sustained observational infrastructure to understand phenomena and build knowledge.

In this view of the value chain linking sustained ocean observing with societal benefit, there are many actors at the basin, regional and national scales. The societal drivers for sustained observations are, in some cases, identified in global and regional conventions, agreements, or regulations that touch on the ocean environment.

There are three broad areas where sustained ocean observations can bring societal benefit:

- Climate: the ocean is a key component of the climate system and influences its evolution and change through the energy, water, and carbon cycles - better monitoring and knowledge will inform both mitigation and adaptation to climate change as well as improved climate services.
- Operational ocean services: coastal populations and infrastructure are growing and are increasingly exposed to ocean-related hazards, and marine industries and users continue to grow - ocean forecasts and early warning systems can help manage risk and improve business efficiency.
- Ocean health: ocean ecosystems are coming under increasing pressure from anthropogenic influence, both through climate change which is warming, acidifying and changing oxygen distributions, as well as through direct human impact - better monitoring and knowledge will help in sustaining livelihoods and ecosystem services from the ocean.

This report identifies in some detail the path within the Framework for Ocean Observing used to identify requirements, starting with these three broad areas of societal benefit and then identifying the specific areas of societal benefit, the scientific issues and applications that inform this benefit, the phenomena of the Atlantic that must be captured, the Essential Ocean Variables, and the observing platforms and networks that are able to capture these variables. In GOOS this is identified as the *Strategic Mapping*, and has been visualized as a Sankey diagram that shows the possible links between nodes, from the main areas of societal benefit through to observing networks measuring EOVs (Figure 3).

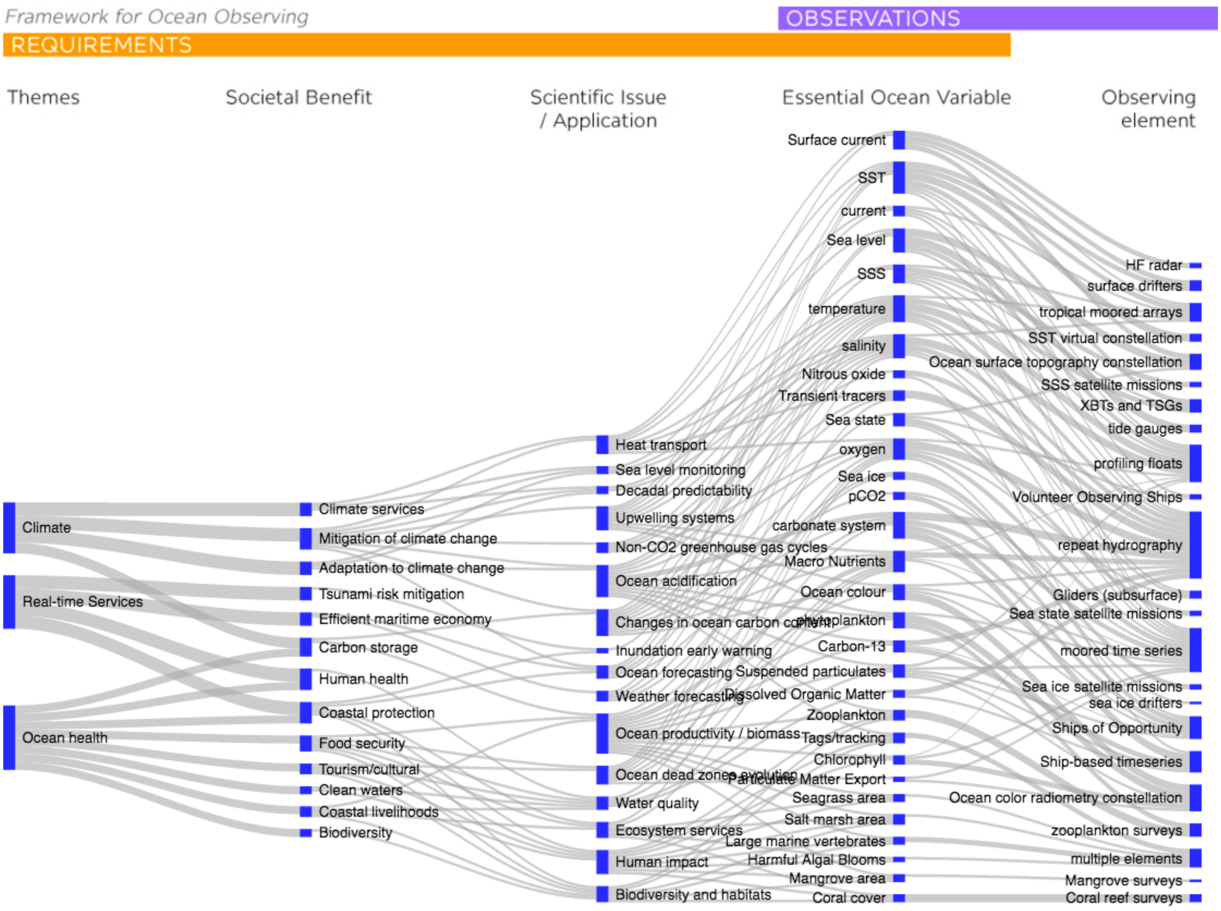


Figure 3: GOOS Strategic Mapping visualization of the connection between major themes of societal benefit (climate, operational ocean services, and ocean health), societal benefits, scientific issues and applications, phenomena (not included in this version of the visualization), Essential Ocean Variables, and observing platforms.

The report draws on existing work, adapted where necessary to the Atlantic:

- the ocean Essential Climate Variables (ECVs) and requirements of the Global Climate Observing System (GCOS), which is in the process of developing a new 2016 Implementation Plan for review and adoption by the UN Framework Convention on Climate Change (UNFCCC) in December 2016,
- the requirements processes of the World Meteorological Organization (WMO) Rolling Review of Requirements, and in particular its focus with the Joint WMO-IOC Technical Commission on Oceanography and Marine Meteorology (JCOMM) on ocean applications related to waves, coastal hazards, sea ice, marine emergency response, and ocean forecast systems,
- work by the Global Ocean Observing System (GOOS) physics, biogeochemistry, and biology and ecosystem panels in the specification of Essential Ocean Variables (EOVs), and assembly into an overall Strategic Mapping,
- the GEO Biodiversity Observing Network (GEO BON) and its work on marine Essential Biodiversity Variables,
- regional sustained ocean observing efforts such as EuroGOOS and the US Integrated Ocean Observing System (IOOS), and
- work under regional and European frameworks to identify indicators in an ecosystem-based approach to management of living marine resources.

This report reflects the geographic and thematic scope of the AtlantOS Project. AtlantOS comprises the Atlantic on a basin scale roughly covering the region south of the Greenland-Scotland Ridge and Labrador Sea, and north of the southern tip of South Africa. And AtlantOS has a primary focus on in situ sustained observations on the basin scale, with a connection to the satellite observations of the ocean surface, and sensitivity to how these basin-scale and regional observations will add to coastal ocean observing systems and services.

The outputs of AtlantOS sustained ocean observations meet the definition of public goods. They are non-rivalrous, that is, they can be consumed by an increasing number of users without devaluing their benefit. They are also in general non-excludable, that is, it is difficult to set up barriers to access to the data, given that the Atlantic Ocean is large, much of it is in areas beyond national jurisdiction, and the basin-scale observing networks are set up on the basis of international collaboration and open exchange. The observations are largely set up at delivering information about common issues, and global or regional scale services: climate, weather, hazards, and the sustainability of ocean ecosystems. And although the quantification of the socio-economic benefit of ocean observations is not widespread, there is a sense that they can have immense value in shaping common policy on climate, the management of shared ocean resources, the preservation of lives and property from ocean-related hazards, and the sustainable use of the ocean. The value chain described above focuses on these public goods, where data has added value from scientific analysis and assessment and public marine core services that can have immediate societal value. That certainly leaves room for private sector innovation to build increased value on top of this public good.

This report is an initial report, based on work initiated outside of the AtlantOS project. It will form the basis of innovation activities within the project and with outside partners, to better define integrated requirements, identify capacities and gaps, trade-offs between the feasibility and impact of different observing networks in capturing Atlantic Ocean phenomena and delivering for scientific and operational applications. It will form a basis for further discussions about common priorities amongst AtlantOS project partners and all stakeholders, around the Atlantic basin, in a future AtlantOS integrated and sustained ocean observing system.

The report identifies the societal drivers for sustained observations in Section 2, the scientific context, applications and phenomena to observe in Section 3, Essential Ocean Variables and their identified readiness in Section 4, and observing elements for AtlantOS in Section 5. Section 6 outlines some of the challenges in improving the definition of requirements during the course of the AtlantOS project.

2 Societal Benefit Areas and Societal Drivers for Sustained Observations

The three major areas of societal benefit related to sustained ocean observations - climate, operational ocean services, and ocean health - were identified in the introduction.

In 2015, each of these areas was the subject of a global agreement or framework:

- The UNFCCC's Paris Agreement adopted by COP-21 in December 2015 sets out an ambitious climate agenda with a formal limit to the increase in the global average temperature to “well below 2 °C”, noting the importance of "ensuring the integrity of all ecosystems, including oceans", and recognizing the importance of "systematic observation" in the context of climate change adaptation, and insisting that actions must be taken in accordance with the "best available science."
- The Sendai Framework for Disaster Risk Reduction 2015–2030 is the principal outcome of the 3rd UN World Conference on Disaster Risk Reduction (14–18 March 2015, Sendai, Japan), which focuses on understanding disaster risk, strengthening governance, investing in risk reduction and

preparedness. In this context operational ocean services focused on coastal and marine hazards are very relevant.

- The UN Sustainable Development Goal 14 "Converse and sustainably use the oceans, seas and marine resources for sustainable development" is fundamentally related to monitoring of ocean health.

These are illustrations that the global ocean, of which the Atlantic is a significant and interconnected part, is of growing policy importance in the context of environmental, developmental, and risk management agendas.

This section identifies how sustained ocean observations are important to these three broad societal benefit areas, as well as to the eight GEO Societal Benefit Areas that are identified in the *GEO Strategic Plan 2016-2025: Implementing GEOSS.*

2.1 Climate

2.1.1 Climate: global drivers related to climate change and climate services

The global ocean has a profound and multidimensional influence on planetary conditions, interacting with Earth's atmosphere, cryosphere, land, and biosphere. It also directly influences human welfare through the provision and transport of food and resources, as well as by providing cultural and economic benefits.

Mitigation of climate change

Given the negative impact of anthropogenic climate change (including sea level rise, droughts, hurricanes & flooding, reduction of biodiversity, impact on fisheries, and the creation of urban heat waves), immediate actions to mitigate climate change are required. The core action is focused now on implementation of the Paris Agreement, as noted above. The ocean already plays an important role in the context of mitigation of climate change, on global and basin scales as well as in coastal areas. The oceans have taken up more than 90% of the excess heat originating from the heat imbalance due to the emission of greenhouse gases, and monitoring of ocean heat is therefore a key indicator of the state of the climate system, more reliable than monitoring of global mean surface temperature.

The ocean is also an important sink for excess carbon dioxide and other greenhouse gases, and thus moderates even more this global heat imbalance. Given the Paris Agreement's goal of keeping warming to well below 2°C and its insistence on basing action on the best available scientific knowledge, it is important to monitor the continued uptake of anthropogenic carbon by ocean sinks, and to monitor whether changing climatic conditions change any of the ocean sources of greenhouse gases, such as methane.

This also includes the monitoring of the extent and condition of the natural coastal ecosystems - seagrasses, tidal marshes and mangroves - that store large amounts of carbon in their roots, stems and leaves and sequester it for decades or centuries in the sediment. When these habitats and sediments are preserved, air cannot reach the carbon they store. If they are disturbed or destroyed, air reaches the carbon and oxygen oxidizes it to carbon dioxide (CO_2), a heat-trapping gas that is the main source of climate warming.

Recommendations by the Global Forum on Oceans, Coasts, and Islands for the UNFCCC process include the need for properly regulating mitigation efforts using the oceans. Mitigation of the negative consequences of climate change involving the oceans should be carefully scrutinized and viable measures encouraged through appropriate regulatory frameworks. Carbon capture and storage (CCS), for instance, has potential as a mitigation measure, but needs to be carefully studied and regulated to ensure safe and effective practice in order to minimize the societal risks and maximize the societal benefits. A sustained observing network capable of monitoring ocean carbon and biogeochemistry is essential to meeting both the scientific and regulatory need of the requirement for climate change mitigation using the oceans.

As stated in the Intergovernmental Panel for Climate Change (IPCC) Fifth Assessment Report (AR5), there is high confidence in the prediction that the removal of human-emitted CO_2 from the atmosphere by natural processes will take a few hundred years, making anthropogenic climate change irreversible on human time scales. Unconventional Carbon Dioxide Removal (CDR) methods, or geoengineering, would likely need to be deployed at large-scales for at least a century to significantly reduce atmospheric CO_2. Nonetheless, there is currently a low level of confidence regarding the side effects of CDR methods on carbon and other biogeochemical cycles, with their marine component constituting a large source of uncertainty.

The main pathway for ocean information to influence policy on mitigation is through the scientific assessments of the IPCC, informing a policy cycle that is embodied by the actions of the UNFCCC.

Adaptation to climate change

The level of anthropogenic greenhouse gasses in the atmosphere and the inertia of the climate system have committed human society to a century or more of climate change, even if greenhouse gas emissions were mitigated completely and immediately.

We therefore need the tools and applications required to manage successful strategies for society to adapt to a changing environment. To successfully adapt today's society to an environment changing due to climate change, we will need actionable information on the effects of greenhouse gases, temperature rise, sea level rise and other known climate change impacts. There is increasing societal demand for more systematic and detailed information on how weather patterns, climate, sea level, ocean conditions and marine productivity are changing (mean and extremes), how they will change in the future (predictions/projections), and what is driving these changes (e.g., understanding of physical mechanisms and the role of human activities and other natural external and internal factors).

How heat is redistributed by ocean circulation and interacts with global energy and water cycles greatly impacts global patterns of rainfall and drought, and better monitoring and knowledge of ocean heat will yield better predictions of global patterns of excess rainfall and drought.

Due also to ocean carbon uptake, the ocean carbonate system is becoming more acidic, which, in turn, has negative impacts on ocean ecosystems and biodiversity. For example, ocean warming reduces the capacity of the ocean to take up oxygen and, in combination with an increase in upper layer stratification, creates, for example, habitat compression that negatively impact fish and fisheries.

As climate change is expected to cause economic loss, adaptation mechanisms are needed. Climate change is, by definition, connected to future evolution of the Earth’s systems and, therefore, on scenarios that can only be tested via science-based climate information and prediction.

The shorter timescales of climate prediction required by adaptation will require better understanding of ocean processes, particularly in the Atlantic Ocean, as well as good monitoring of the ocean state in order to initialize coupled climate forecast systems.

Climate Services

Climate services provide climate information in a way that assists decision-making by individuals and organizations. Such services require appropriate engagement along with an effective access mechanism and must respond to user needs.

Such services involve high-quality data from national and international databases on temperature, rainfall, wind, soil moisture and ocean conditions, as well as maps, risk and vulnerability analyses, assessments, and long-term projections and scenarios. Depending on the user’s needs, these data and information products may be combined with non-meteorological data, such as agricultural production, health trends, population distributions in high-risk areas, road and infrastructure maps for the delivery of goods, and other socio-economic variables.

The WMO Global Framework for Climate Services (GFCS) provides planning, policy, and practice on climate change at global, regional, and national scales. Observations, including ocean observations that are needed for predictions on time scales from intra-seasonal to decadal time scales, are a pillar of the GFCS.

2.1.2 Climate: regional drivers

In Europe, the Copernicus Climate Change Services (CCCS) will become the European Union's major contribution to the WMO GFCS. CCCS defines its role in: informing policy development to protect citizens from climate-related hazards such as high-impact weather events; improving planning of mitigation and adaptation practices for key human and societal activities; and promoting the development of new services for the benefit of society.

CCCS will provide comprehensive climate information covering a wide range of components of the Earth system (atmosphere, land, ocean, sea-ice and carbon) and on timescales spanning decades to centuries (i.e., based on the instrumental record). It will maximise the use of past, current, and future earth observations (from in-situ and satellite observing systems) in conjunction with modelling, supercomputing and networking capabilities. These observations of the climate system will be merged and assessed based on latest science in order to create authoritative, quality-assured information about the past, current, and future states of the climate in Europe and worldwide. The observations required for this service will build upon, and complement, capabilities existing at the national level and being developed through a number of climate-change research initiatives.

For it observational (in-situ and satellite) component, the CCCS relies on multiple Essential Climate Variables that will be used to generate global and regional re-analyses (covering a comprehensive Earth-system domain: atmosphere, ocean, land, carbon). For the ocean, ECVs are similar to EOVs, but uncertainty information is required to qualify these observations to be climate relevant. A data monitoring system that ensures sufficient data coverage is required. CCCS will also produce products such as maps and fields (e.g., gridded; homogenised station series; reprocessed Climate Data Records) that are based on observations alone. A near-real-time climate monitoring facility will be established and multi-model seasonal forecasts and climate projections at global and regional scales will be performed.

2.2 Operational Ocean Services

Those who sail, trade, explore, exploit, relax, and defend their national interests in political, economic, social and environmental issues, are perfectly aware of the importance of the oceans as drivers for the economy and its great potential for innovation and growth. The focus on the business development of marine industries without compromising the vulnerable marine environment, security and efficiency of operations puts strong demands on the availability of reliable operational meteorological and oceanographic products and services. These products and services are based on systematic and long-term routine measurements of the seas, oceans, and atmosphere, and the rapid interpretation and dissemination of data, information, and products. Important products are:

- nowcasts, providing the most usefully accurate description of the present state of the sea including living resources,
- forecasts, providing continuous forecasts of the future condition of the sea for as far ahead as possible, and
- hindcasts, assembling long term data sets which will provide data for description of past states, and time series showing trends and changes.

2.2.1 Operational Services: Global

On a global level, requirements for operational ocean services are captured in the World Meteorological Organization (WMO) Rolling Review of Requirements, and in particular its Statement of Guidance for Ocean

Applications. Marine Meteorology and Oceanography occupy a global role, serving a wide range of users, from international shipping, fishing and other met-ocean activities on the high seas, to the various activities that take place in coastal and offshore areas and on the coast itself. In preparation of analyses, synopses, forecasts and warnings, knowledge is required of the present state of the atmosphere and ocean. The three major met-ocean application areas that critically depend on highly accurate observations of met-ocean parameters are: Numerical Weather Prediction, Seasonal to Inter-annual Forecasts, and Met-Ocean Forecasts and Services (MOFS), including marine services and ocean mesoscale forecasting.

These marine services include:

- managing tsunami and coastal inundation risk from storm surges,
- marine services aimed at the safety of life and property at sea and in coastal areas,
- sea ice services,
- supporting an efficient maritime economy through ocean condition and forecasting services for shipping, marine industries, ocean structures, renewable energy applications, search and rescue, and defense operations.

2.2.2 Operational Services: Atlantic region

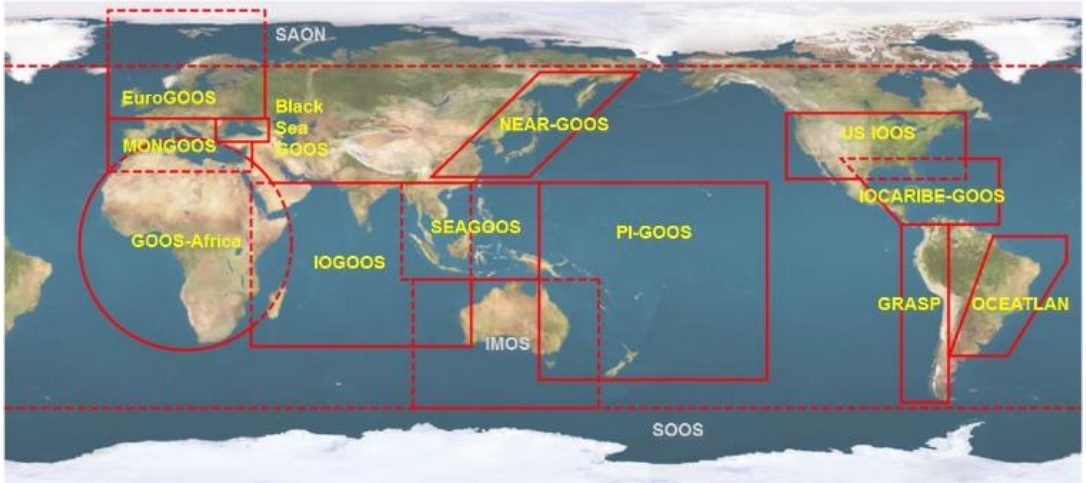


Figure 4: The GOOS Regional Alliances

Globally, operational ocean observations are coordinated within the Global Ocean Observing System (GOOS) which is implemented via activities within 13 GOOS Regional Alliances (GRAs, Figure 4). For the Atlantic Ocean the following GRA's are of relevance: EuroGOOS, IOOS, IOCARIBE GOOS, OCEATLAN and GOOS Africa. The strategies, and the way the work is organised with individual GRAs, differ greatly, as noted below.

Figure 5: GOOS observations from global networks and EuroGOOS in the Atlantic Ocean.

EuroGOOS

The European Global Ocean Observing System (EuroGOOS) is an international non-profit association (AISBL - Association Internationale Sans But Lucratif) of 39 members from 19 European countries, committed to European scale operational oceanography and ocean observing systems within the context of IOC/GOOS. EuroGOOS is organised around five Regional Operational Oceanography Systems (ROOSs), including the Ireland-Biscay-Iberian area (IBI-ROOS) in the European Atlantic Ocean, five working groups and 6-7 observational Task Teams (growing). The EuroGOOS Stregegy 2014-2020 is centered around five key actions:

- define strategies for operational oceanography in Europe
- promote operational oceanography
- foster cooperation in Europe and globally
- initiate coproduction
- work towards establishing a sustained ocean observing system

EuroGOOS is strongly engaged in ensuring all European ocean observing data is made freely available to marine users to support good and sound decision making. Data are made available via central European portals such as the Copernicus Maritime Environmental System (CMEMS), the European Marine Observation and Data Network (EMODnet), or SeaDataNet, but a central component in the data flow from originator to these databases is the EuroGOOS ROOSs cooperation and data exchange system.

EMODnet real-time data in the Atlantic

To fulfil the last key action in the EuroGOOS strategy - the establishment of a sustained ocean observing system - EuroGOOS has, in close cooperation with the European Marine Board, taken the lead in defining and establishing a European Ocean Observing System (EOOS). EOOS is intended to be a sustained and integrated observing system for Europe's seas in order to understand the current state and key processes that underpin the sustainable management of marine resources. EOOS relies on a continuous dialogue with all stakeholders and the inclusion of user requirements to provide services adequate for societal needs, and the outcome of the AtlantOS project will constitute a valuable input to the planning and design of EOOS.

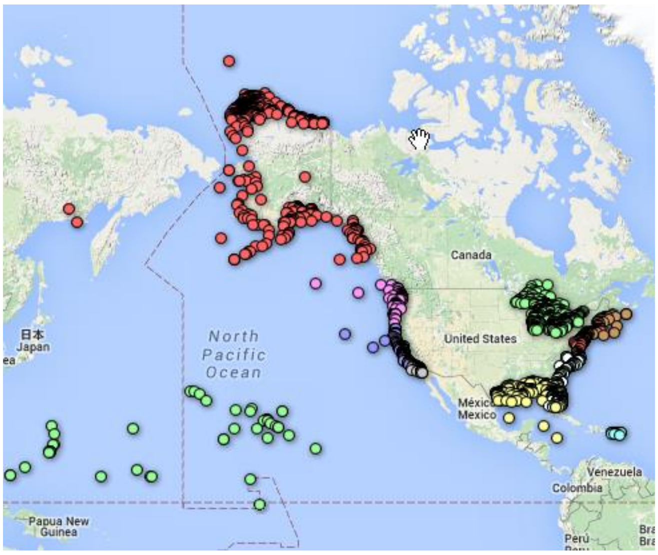


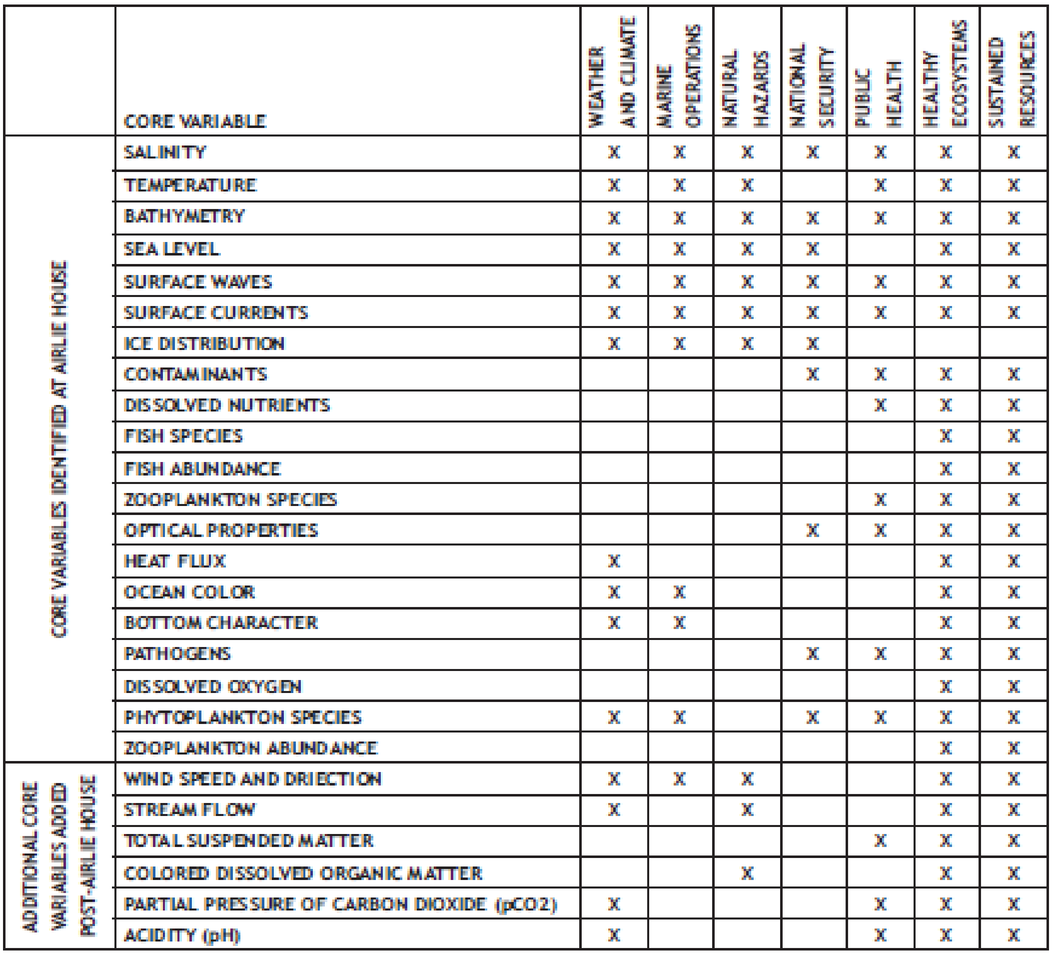
Figure 6: IOOS observations.

IOOS

The U.S. Integrated Ocean Observing System (IOOS®), led by NOAA represents a national consortium of governmental and non-governmental stakeholders, with specific interest in marine environmental phenomena occurring in the open ocean, U.S. coastal waters, and the Great Lakes. The core mission of the U.S. IOOS is the systematic provision of ready access to this marine environmental data and data products in an interoperable, reliable, timely, and user-specified manner to end users and customers in order to serve seven critical and expanding societal needs:

- detect and forecast oceanic components of climate variability
- facilitate safe and efficient ocean operations
- ensure national security
- manage resources for sustainable use
- preserve and restore healthy marine ecosystems
- mitigate natural hazards
- ensure public health

IOOS is a national priority activity established under the "Integrated Coastal Ocean Observation System (ICOOS) Act" signed in 2009. IOOS is comprised of eleven Regional Associations (RAs), which are networks of regional partners responsible for regional observations, data management, modelling and analysis, education and outreach, and research and development. The activities are coordinated and led by the IOOS Program Office established under NOAA. IOOS has an annual budget of approximately 36 million US dollars.



	CORE VARIABLE	WEATHER AND CLIMATE	MARINE OPERATIONS	NATURAL HAZARDS	NATIONAL SECURITY	PUBLIC HEALTH	HEALTHY ECOSYSTEMS	SUSTAINED RESOURCES
CORE VARIABLES IDENTIFIED AT AIRLIE HOUSE	SALINITY	X	X	X	X	X	X	X
	TEMPERATURE	X	X	X		X	X	X
	BATHYMETRY	X	X	X	X	X	X	X
	SEA LEVEL	X	X	X	X		X	X
	SURFACE WAVES	X	X	X	X	X	X	X
	SURFACE CURRENTS	X	X	X	X	X	X	X
	ICE DISTRIBUTION	X	X	X	X			
	CONTAMINANTS				X	X	X	X
	DISSOLVED NUTRIENTS					X	X	X
	FISH SPECIES						X	X
	FISH ABUNDANCE						X	X
	ZOOPLANKTON SPECIES					X	X	X
	OPTICAL PROPERTIES				X	X	X	X
	HEAT FLUX	X					X	X
	OCEAN COLOR	X	X				X	X
	BOTTOM CHARACTER	X	X				X	X
	PATHOGENS				X	X	X	X
	DISSOLVED OXYGEN						X	X
	PHYTOPLANKTON SPECIES	X	X		X	X	X	X
	ZOOPLANKTON ABUNDANCE						X	X
ADDITIONAL CORE VARIABLES ADDED POST-AIRLIE HOUSE	WIND SPEED AND DRIECTION	X	X	X			X	X
	STREAM FLOW	X		X			X	X
	TOTAL SUSPENDED MATTER					X	X	X
	COLORED DISSOLVED ORGANIC MATTER			X			X	X
	PARTIAL PRESSURE OF CARBON DIOXIDE (pCO2)	X				X	X	X
	ACIDITY (pH)	X				X	X	X

Table 1: The 26 Essential Ocean Variables that IOOS has defined to meet its 7 societal needs. An x denotes where IOOS produces real-time ocean observations. Notice that IOOS observations are concentrated primarily in US national waters, and there are no data from the open Atlantic Ocean.

IOCARIBE GOOS

IOCARIBE GOOS was formed in 1999 and has 7 member countries. Activities have been relatively few due to a lack of funding. IOCARIBE GOOS has, however, built an extensive network of tide gauges, primarily as a part of a tsunami early warning system. In close cooperation with IOOS, a national Coastal GOOS system for small islands is being developed and implemented at Puerto Rico and the US Virgin Islands.

OCEATLAN

OCEATLAN is an association of institutions from Brazil, Uruguay, and Argentina cooperating on ocean observations in the southwestern Atlantic Ocean, north of 40°S. In addition to coastal observations, it plays a role in the deployment of the PIRATA tropical moored array in the Atlantic and in Argo floats.

IOCAFRICA-GOOS

IOCAFRICA-GOOS is an established GOOS Regional Alliance with semi-regular meetings but the coordination of operational ocean observing activity is still in the preparatory phase. Coordinated national observation programmes in the region are minor and primarily focused in the coastal regions.

Canada

Canada is preparing development of a Canadian integrated ocean observing system that will have projection into the Atlantic Ocean.

Conclusions

A majority of the operational observing activities of GRAs within the Atlantic region are concentrated on the northern hemisphere, and primarily within the 200nm zone. Argo float observations partially complement this in the open ocean, but there remains a great need to find ways to establish operational ocean observation networks in the open ocean part of the Atlantic as a supplement to the Argo system as well as in the national waters of the countries in the southern Atlantic.

2.2.3 Operational Services at European Level

Marine operational services in Europe shall meet a wide range of user requirements in many different maritime sectors. A preliminary approach to define these user requirements, as well as to determine the appropriateness of the available ocean data, has already been initiated in the framework of the Copernicus Marine Environmental Monitoring Service (CMEMS), in the EMODnet sea-basin checkpoints for the European Seas, and also in the Framework for Ocean Observing (FOO) of real-time services of the Global Ocean Observing System (GOOS).

In the CMEMS, in-situ marine observations, satellite data, and operational numerical model products (i.e. state-of-the-art model re-analyses and forecasting) shape the core services for different social benefit areas related to marine activities, with users ranging from the public sector to industry. CMEMS provides information to four areas of benefits: Maritime Safety, Coastal and Marine Environment, Marine Resources, and Weather Forecasting. Each of these four areas comprise at-sea activities that require operational marine services:

1. Many activities within Maritime Safety rely on marine operational services: shipping route optimisation (particularly in ice-covered regions), offshore operations, oil spill response and remediation, and search and rescue activities. Each of these require real time observations and model forecasts of several physical parameters (i.e., waves, currents, temperature, sea ice extent and concentration, sea level, or wind over the sea). Primary examples of public users of these services are the EMSA (European Maritime Safety Agency), the regional conventions for European waters in the Atlantic Region (OSPAR), and national maritime safety agencies with responsibilities in search and rescue and combatting marine pollution. In addition, private users, including environmental or engineering consulting companies that offer downstream services in Europe, can greatly benefit from these marine operational services.
2. The Marine Resources area encompasses all activities related to the protection and sustainable management of living marine resources. Examples include fisheries management, sustainable aquaculture, and fisheries research. The information required for these activities are mainly physical parameters (i.e., ocean currents, temperature, and sea level) but also biogeochemical parameters (e.g., chlorophyll, dissolved oxygen, and nutrients). Key users are ICES (International Council for the Exploitation of the Sea), NAFO (North Atlantic Fisheries Organisation), and FAO (Food and Agriculture Organization of the United Nations), as well as national fisheries agencies. Operational oceanographic products are also used by the commercial fishing fleet to plan their activities, since individual fish stocks prefer different temperatures, fronts, upwelling areas, etc.
3. Appropriate management of the Coastal and Marine Environment requires real time oceanographic products for a wide range of activities: water quality monitoring and pollution control in coastal waters, particularly in the context of the European Marine Strategy Framework Directive (MSFD); monitoring of the bathing water quality for tourism activities; coastal erosion and sediment transport; tsunami warning; storm surge; and site selection for installation of the infrastructures needed to explore, exploit and extract oil, gas, other energy resources, minerals, and aggregates, and to produce energy from renewable sources (e.g., offshore windmill parks or thermal energy conversion fields). The ocean parameters required for these activities are mainly physical (waves, currents, temperature, and sea level) but also include biogeochemical parameters such as

chlorophyll, dissolved oxygen, and nutrients. Key public sector users are the EEA (European Environmental Agency), the regional conventions for European waters in the Atlantic Region (OSPAR), and national environmental public agencies. Private users include environmental and coastal engineering consulting companies offering downstream services to oil and gas and mineral extraction and renewable energy companies.

4. Short-term Weather Forecasting also benefits from operational marine services because physical parameters of the ocean surface are used as bottom boundary conditions for weather forecast models. CMEMS operational service delivers reliable and robust data (mainly waves, currents, temperature, salinity, sea ice, and sea level) to the European and national meteorological services. Key users of this service are the national weather services and private companies dealing with weather forecast services.

Case Study: Fishing Industry

The fishing industry requires standard weather forecasting and sea state products. The state of the science is not yet sufficiently advanced to directly aid in the catching of fish using specific products such as likely distribution or shifts in fished species. Shifts are not just a reflection of moving fish but also of the changes in productivity of those fish stocks. Shifts would also impact the management of the fisheries under the Common Fisheries Policy (CFP) of the EU. Shifting stocks could impact the relative stability of the catch distribution across countries and fleets (i.e., the way the allowable catches are divided up between countries). However, as noted above, the inability to forecast these shifts limits the effective utility of services.

Adequacy of Current Operational Services

Under the framework of the EMODnet sea-basin checkpoints project, of which one focus on the Atlantic Ocean, a literature survey was carried out to determine if existing marine operational services and available marine data fulfil all the requirements for a set of key societal applications or “*challenges*”. These societal challenges, the main societal *drivers* for a sustained observation system and the associated marine operational services, have been defined to be: windfarm siting, marine protected areas, oil platform leaks, climate, coastal protection, fisheries management, fishery impacts, marine environment, eutrophication, bathymetry, river inputs, and alien species. Each of these challenges falls within one of the four general areas of benefits served by the CMEMS services described above. The literature survey revealed that these challenges often require more operational information than provided by CMEMS. Therefore, the EMODnet Sea Basin Checkpoints project has served as a step in a process to determine in more detail which are the main priorities for ocean observations and the requirements for operational marine services.

Only some of the Checkpoint challenges require marine operational services; the remaining challenges rely mostly on ocean data in delayed mode or on ocean model re-analysis. The challenges requiring operational services, and the required parameters, are:

- Windfarm sitting (Coastal and Marine Environment benefit area): sea level, water temperature, water salinity, water velocity, wave parameters.
- Marine protected areas (Coastal and Marine Environment benefit area): oxygen, pollutants in sea water, chlorophyll, transparency, sea level, water temperature, water salinity, water velocity, light penetration, wave parameters
- Oil platform leak (Marine Safety benefit area): water currents, water temperature, wave parameters
- Coastal protection (Coastal and Marine Environment benefit area): sea level, wave parameters
- Eutrophication (Coastal and Marine Environment benefit area): chlorophyll, light, oxygen, temperature, salinity.

The GOOS Strategic Map also defines a set of societal benefits that require operational marine services:

- Tsunami warning and mitigation (Coastal and Marine Environment benefit area)
- Efficient maritime economy (Marine Safety benefit area)

- Human health (water quality societal benefit defined in CMEMS)
- Coastal protection (Coastal and Marine Environment benefit area)

Near real-time observations products, together with ocean forecasts, provide the operational information needed by different users in the public and industry maritime sector. Different users require different spatial and temporal resolution and accuracy, with timescales ranging from seconds to days and spatial scales ranging from a few hundred meters to several km. The spatial and temporal resolution requirements for model outputs and observations depend on the scale of the ocean phenomena needing to be resolved and predicted. For instance, high model resolutions (less than 5 km and hourly) are necessary to resolve meso- and sub-mesoscale structures on the ocean circulation and its variability, essential to accurately predict three dimensional dispersions of particles and pollutants in the sea. Resolutions of less than 1 km are needed to resolve the sea level and wave parameters necessary for accurate storm surge and wave modelling for coastal extreme events.

The strong impact of in-situ (physical and biogeochemical) observations on the quality of marine services, including in those provided by forecasting ocean models, implies that the design of observing networks must be considered carefully. In particular, the impact of temporal and spatial resolution (i.e., spatial distribution and temporal sampling) at which EOVs are acquired is an open and very important question which will be evaluated by means of OSE (Observing System Experiment) and OSSE (Observing System Simulation Experiments) experiments performed by the modelling community, and will help determine the optimal temporal distribution and temporal sampling of the in-situ observations.

2.3 Ocean Health

As the world moves toward a blue economy, reliable information to inform decision-making is increasingly important. By 2030, two out of every three fish consumed will have been farmed, much of it in the sea and offshore wind capacity is forecast to rise almost tenfold by 2030. Seaborne trade is expected to quadruple by 2050. Already, about half of the world's population live along or within 200 km of a coastline on just 10% of the earth's land area; this proportion will only increase with continued urbanization. Balancing economic activity with the a resilient and healthy ocean ecosystem (i.e., the blue economy) will require improved governance and planning, which will necessitate improved, sustained, and integrated monitoring efforts, accessible data, and applications.

Recognising the importance of maintaining ocean health and the role of the ocean in providing ecosystem services and societal benefits, a number of international and regional conventions have recently been implemented. These agreements, some binding, focus on a wide range of issues, from biodiversity to sustainable development; a number of examples are provided below.

2.3.1 Global Agreements

The Convention on Biological Diversity (CBD) has three main goals: conservation of biological diversity; sustainable use of its components; and fair and equitable sharing of benefits arising from genetic resources. As part of the CBD's Decade of Biodiversity (2011-2020), the Aichi Biodiversity Targets were developed, comprising 20 targets within 5 strategic goals; specific targets include integrating biodiversity values into national and local development and poverty reduction strategies; having all fish and invertebrate stocks and aquatic plants managed and harvested sustainably, legally and applying ecosystem based approaches; and conserving 10 per cent of coastal and marine areas. In 2015, the United Nations adopted 17 Sustainable Development Goals (SDGs) as part of its 2030 Agenda for Sustainable Development; SDG 14 ("Conserve and sustainably use the oceans, seas and marine resources for sustainable development") comprises 10 targets dealing with pollution, sustainable management of ecosystems, ocean acidification, fishing practices, conserving at least 10% of marine and coastal areas, and the transfer of marine science and technology.

Other international agreements of relevance to ocean health include those from the International Seabed Authority, the International Maritime Organization (e.g., pollution), the UNEP Global Program for Protection of the Marine Environment from Land-Based Activities, and the Food and Agriculture Organization (FAO).

The GOOS Biology and Ecosystems Panel is in the process of analyzing 24 global and regional agreements or international bodies that identify the need for sustained monitoring of ocean ecosystems or biological variables, in order to extract the key Drivers for observations and the Pressures identified of human impact on marine biodiversity and ecosystem health. Their concept is to use a Drivers-Pressures-State-Impact-Response (DPSIR) framework to identify the requirements for sustained monitoring of biological and ecosystems Essential Ocean Variables. The major drivers for observations across these agreements are (in decreasing order):

- Knowledge: developing the scientific knowledge and data access to allow for pressures to be better understood,
- Sustainable use of biodiversity and living marine resources,
- Conservation of biodiversity and ecosystems,
- Improving management through integrated ecosystem approaches,
- Sustainable economic growth and development,
- Capacity building,
- Threat prevention and impact mitigation,
- Environmental quality and protecting health, and
- Food security.

The major pressures on ocean ecosystems were identified as (in decreasing order):

- loss of resources of habitats and biodiversity, including through overfishing,
- climate change,
- pollution and eutrophication,
- coastal development,
- invasive species,
- solid wastes,
- ocean acidification,
- extreme weather events,
- noise, and
- mining.

2.3.2 Regional Agreements

Regional Fisheries Management Organisations (RFMOs) are international organizations dedicated to the sustainable management of fishery resources in a particular region of international waters, or of highly migratory species. They may focus on certain species of fish (e.g., the The International Commission for the Conservation of Atlantic Tunas) or on a geographical region (e.g., the Northwest Atlantic Fisheries Organization (NAFO)). While some RFMOs have a purely advisory role, most have management powers to set catch and fishing effort limits, technical measures, and control obligations.

The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) regulates cooperation on the protection of the marine environment in the North-East Atlantic and includes annexes on dumping at sea, land-based sources, biodiversity and ecosystems, and impacts from non-polluting human activities. It is guided by an ecosystem approach to the integrated management of human activities and requires that Member States apply the precautionary and polluter-pays principles. Its Quality Status Report 2010, a comprehensive assessment which examined all aspects of human influence on the sea (including contaminants, nutrient pollution and radioactive substances and the effects of human activities such as the offshore oil and gas industry, offshore wind farms, maritime transport, and fisheries), indicated that while there were improvements in reducing human impacts in many of these areas, improvements were still needed, particularly in the area of fisheries management. OSPAR updates this report with assessment sheets, e.g., the Status of the OSPAR Network of Marine Protected Areas in 2014.

The International Council for the Exploration of the Sea (ICES), a network of more than 4000 scientists from over 350 marine institutes in 20 member countries and beyond, develops science and advice to support the sustainable use of the oceans. It provides unbiased scientific advice to member nation governments and international regulatory commissions in support of the management and conservation of coastal and ocean resources and ecosystems. For example, advice on the management of finfish and shellfish stocks is provided to the European Commission (EC) and scientific information on anthropogenic impacts to the marine environment are provided to the Commission for the Protection of the Marine Environment of the North-East Atlantic (OSPAR).

2.3.3 Europe

The Marine Strategy Framework Directive (MSFD), the environmental component of Europe's Integrated Maritime Policy aims to protect the marine environment across Europe. It is designed to create a framework for sustainable use of Europe's marine waters, mandates an Ecosystem Approach to management and sets a target of "Good Environmental Status" which must be achieved in EU marine waters by 2020. Each Member State must pass targets in 11 areas, including biodiversity, safeguarding commercial species, eutrophication, contaminants, marine litter, and energy and noise.

2.3.4 Overall: sustaining and using ocean ecosystem services

Overall, the global, regional, and European agreements are focused on the sustainability or optimal use of ocean ecosystem services. Halpern et al. (2012) identify a set of targets focused on ocean ecosystem services, and these services are summarized in the GOOS *Strategic Mapping* as:

- Coastal protection: Habitats such as mangrove forests, seagrass meadows, salt marshes, tropical coral reefs, and sea ice protec the coasts against storm waves and flooding. Storm protection by coastal habitats saves lives, property and is worth billions of dollars each year.
- Protecting human health: Maintaining a healthy oceanic environment protects human health by avoiding pathogens, pollution and tainted seafood
- Food security: Food Security includes ensuring the sustainability of all forms of natural resource use for human consumption, such as fisheries and mariculture.
- Preserving coastal livelihoods: Half the world’s fish harvest is captured by artisanal fishing families on a small, local scale. From seashells and sponges to aquarium fish, natural products contribute to local economies and international trade. Monitoring these resources helps protect coastal livelihoods.
- Biodiversity: People value the existence of a diverse array of species for their intrinsic qualities and their contributions to the structure and function of resilient ecosystems.
- Tourism and Culture: Improving the experience people have visiting coastal and marine areas and attractions. Maintaining the attraction of coastal destinations: Coastal and marine tourism is a vital part of a country’s economy. Protecting iconic species and special places: People derive a sense of identity or value from living near the ocean, visiting coastal or marine locations or just knowing that such places and their characteristic species exist.

Further work is needed to harmonize the approaches taken at the global, regional, and national levels to come up with a unique and agreed conceptual framework for the description of the societal benefits and drivers of sustained observations of ocean biology and ecosystems.

2.4 Alignment of Ocean Observations with GEO Societal Benefit Areas

AtlantOS provides a contribution to the Group on Earth Observation (GEO) Global Earth Observing System of Systems (GEOSS) through a consolidation of in situ observations for societal benefit in the Atlantic Ocean, including through GOOS which is a Participating Organization of GEO and through GEO's Blue Planet initiative.

GEO, in its Strategic Plan for 2016-2025 has defined eight Societal Benefit Areas as the domains in which Earth observations are translated into support for decision-making. It identifies climate change as its impacts as cutting across all SBAs. Sustained observations from the ocean have a contribution to make to nearly all of the identified SBAs (identified as strong, medium, or mild based on a judgment of the importance of ocean observations vs. those from other domains, including socioeconomic):

- Biodiversity and Ecosystem Sustainability: the ocean constitutes over 90% of the habitable space on the planet, and the ocean has greater diversity of phyla: 30% of phyla are exclusively marine, while only one phylum is exclusively terrestrial. Ocean ecosystems provide services that range from the universal (50% of the oxygen on earth) to the more specific ones described in the previous section. Marine conservation, sustainable use, and marine spatial planning all require sustained ocean observations. Strong contribution of ocean observations.
- Disaster resilience: Risk of ocean-related hazards at the coast is growing with increased exposure of vulnerable human populations; while weather extremes even far inland can be driven by changing ocean conditions. Strong contribution of ocean observations.
- Energy and Mineral Resources Management: ocean renewable energy is promising but requires ocean information for site development and associated marine spatial planning. Ocean oil and gas exploration and exploitation is growing, and both development and operations depend on reliable ocean information. Medium contribution of ocean observations.
- Food security and sustainable agriculture: Fisheries and mariculture are a growing source of food for human populations, and their sustainable management requires ocean environmental information. Strong contribution of ocean observations.
- Infrastructure and transportation management: ocean conditions impact weather and climate. Mild contribution of ocean observations.
- Public Health Surveillance: Harmful Algal Blooms and ocean pollution can be sources of environmentally-linked disease. Medium contribution of ocean observations.
- Sustainable Urban Development: coastal megacities continue to increase in population, exposing them to sea level rise and extremes risk. Medium contribution of ocean observations.
- Water Resources Management: The oceans are a key part of the global hydrological cycle, and interact with the atmosphere to control patterns of drought and rainfall. Medium contribution of ocean observations.

3 Scientific context, applications and phenomena

This section bridges the broad link between societal benefit and what we should measure in a sustained way in the ocean. It attempts to identify the scientific context, the applications needed to provide societal benefit, and the phenomena that need to be observed in the ocean, which are captured by the Essential Ocean Variables (next section).

The *Applications* are the deliverable information, which is needed to create societal benefits. This information will be actionable by marine managers and ocean users, and based on the best science and observations available. Information can be delivered in near real time, such as by weather and ocean forecasting, or can be compiled for continuous use, such as water quality estimates or knowledge of ocean dead zones. Applications may be thought of as integrative marine models and tools that bring together knowledge of multiple phenomena as components.

The *Phenomena*: the science which underpins the applications is based on understanding and building intermediate tools and models, such as estimates of air-sea fluxes, sea level changes, status of food webs etc. Each phenomenon should be described using one or a number of Essential Ocean Variables. Phenomena are intellectual integrations of interactions in the natural system, brought together to form a useful product that can be used with other phenomena in creating management tools or applications. Particularly when moving to the biological and ecosystems space, phenomena may be quite broad and represent indices. Their usefulness often comes by monitoring their variation through time. Indeed, time variation is the essence of the need for sustained observation systems.

The space and time scales as well as the variables that help describe a phenomenon are important to identify in order to develop traceability in requirements placed on the observing system. This traceability to specific applications and phenomena is important when setting priorities. However, it is also important to understand that this abstraction helps identify areas of integration in the observing system, where requirements linked to specific applications and phenomena overlap.

3.1 Overview of the applications and phenomena

The value chain in Figure 2 introduced the concept of the importance of ocean research and technology innovation in helping to develop the sustained ocean observing system, but also that there is an important pathway to societal benefit that is based on scientific analysis and assessment that is then delivering policy-relevant science.

An initial analysis of the work of the GOOS Panels in the table below shows the link between societal benefit *(rows)* and applications *(columns),* many of which are set in scientific context through assessments.

	Climate Forecasting and Projection	Climate analysis and assessment	Climate Cycles	Weather forecasting	Ocean forecasting	Ecosystem Assessment	Biodiversity Assessment	Sustainable Management	Pollution Assessment	Marine Hazard Response	Assessing Human Impact on Ocean
Climate Mitigation	X	X	X	-	-	-	-	-	X	X	-
Climate Adaptation	X	X	X	-	-	X	-	X	X	X	-
Climate Services	X	X	X	X	-	-	-	X	-	-	-
Tsunami and Inundation Risk	-	-	-	X	X	-	-	-	-	X	-
Marine Services	-	-	-	X	X	-	X	-	-	X	-
Efficient Maritime Economy	-	-	-	X	X	X	-	X	X	X	X
Coastal Protection	-	-	-	-	X	-	-	X	-	X	-
Human Health	X	-	-	X	-	X	-	X	-	X	X
Food Security	-	-	-	X	X	X	X	X	X	-	X
Coastal Livelihoods	-	-	-	-	-	X	X	-	X	X	-

Sustainable Ocean Health	-	-	-	-	-	X	X	-	X	-	X
Biodiversity	-	-	-	-	-	X	X	-	-	-	-
Tourism and Culture	-	-	-	X	-	-	X	X	-	-	X
Clean Waters	-	-	-	-	-	-	-	X	-	-	X
Human Impacts	-	-	-	-	-	-	-	-	-	X	X

The applications *(rows)* can then be shown with their links to the major phenomena *(columns)* that need to be captured, in the table below:

	Extreme Events	Sea Level	Circulation	Fronts / Eddies	Tides	Near Inertial Oscillations	Heat Storage	Air-sea fluxes	Mixed Layer	Stratification	Upwelling	Water Mass	Riverine	Freshwater Cycle	Surface Waves	Sea Ice Extent	Coastal Processes	Ocean Acidification phenomena	Ocean Carbon Cycle	non-CO2 greenhouse gas cycles	Eutrophication hypoxia	Ocean productivity	Particle concentrations	Particulate Matter Transport	Habitat modification	Food webs	Contaminants Sources/Transport	Contaminant sinks / transformation	Pollution Impacts
Climate Forecasting and Projection	-	-	X	-	-	-	X	X	X		-		-		-	-	-	X	X	-	-	-	-	-	-	-	X	-	-
Climate analysis and assessment	-	-	-	-	-	-	-	-	-		-		X		-	-	-	-	X	-	-	-	-	X	-	-	-	X	X
Climate Cycles	-	-	X				-	-	-		X		-		-	-	-	X	X	X	X	-	-	X	-	-	X	X	-
Weather forecasting	X	-	-				X	X	X		-		-		X	X	X	-	-	-	-	-	-	-	-	-	X	-	-
Ocean forecasting	X	X	X				X	X	X		X		X		X	X	X	-	-	X	-	-	-	X	-	-	X	-	X
Ecosystem Assessment	-	-	-				-	-	-		-		X		-	-	-	X	X	X	X	X	X	X	-	X	X	X	X
Biodiversity Assessment	-	-	-				-	-	-		-		-		-	-	-	X	-	-	X	X	-	X	X	X	X	X	X
Sustainable Management	-	-	X				-	-	-		X		X		-	-	-	-	-	-	X	X	X	-	-	-	X	-	X
Pollution Assessment	-	-	X				-	X	-		X		X		-	-	X	X	-	-	X	-	X	X	-	-	X	X	X
Marine Hazard Response	X	X	X				-	-	-		-		-		X	X	X	-	-	-	X	-	-	-	X	-	-	X	X

Assessing Human Impact on Ocean	-	-	-				-	-	-		-		X		-	-	-	-	-	X	-	X	-	X	X	X	-	X	X

The link between phenomena and Essential Ocean Variables can be found in Section 4.

The scientific context is particularly important for the value chain pathway through assessment, and so for issues related to climate and to biodiversity and ecosystems.

3.2 Atlantic phenomena to observe: climate

3.2.1 Physical

A wide range of Atlantic phenomena are coupled to the meridional transport of heat and freshwater. The South Atlantic is the only basin with an equatorward heat transport that further more links to the northward propagation of heat, which in turn moderates the climate in Europe. In the context of the South Atlantic mesoscale eddies (Agulhas rings) play an important role. The impact of NAO and longer (AMO) atmospheric variability on the ocean circulation (including the wind-driven and thermohaline component) also control the meridional mass and property transport. On a regional scale this introduces variability of major currents, e.g. as the Gulf Stream which in turn impact the ecosystems, but also local sea-level changes. In response to ocean bottom water warming the release of carbon dioxide from hydrocarbon reservoirs is expected. This process can impact not only atmospheric carbon dioxide (and methane) concentrations but can have regionally and impact on the maritime safety.

Other modes of tropical climate variability are often a more direct ocean atmosphere interaction and closely related to severe flooding and droughts. As such it is desired to monitor and predict the ocean state and evolution on time scales of up to a year or so. Given the dynamics of the tropical oceans, dedicated observing systems, such as the PIRATA system in the tropical Atlantic, can provide the critical information that is required for estimating the initial fields and predicting the future evolution.

Changes in sea ice coverage as well as land ice coverage are of crucial importance of their feedback on radiation (albedo) but also has impact on ecosystems in the Arctic domain. Melting of land ice lead to increase in sea level – this increase in freshwater volume add to the sea level rise through the thermosteric extension of the sea water under a warming climate.

Other interaction of climate and regional scales are mediated by changes in frontal structures (with impact on biogeochemistry, ecosystems). Planetary waves, crucial for the processes in the tropical ocean, also play a role in other latitudes and interaction with long term changes e.g. of gyre axis alignments which in turn can only be disentangled by appropriate sampling. Here the propagation of property anomalies into coastal areas is of crucial importance for the coastal ecosystems.

The process that is responsible for the ocean uptake of heat and greenhouses gases is the water mass formation that ventilates the interior ocean on time scales longer than one year (one season). The primary processes are deep convection and subduction and which are linked to the surface buoyancy and wind/momentum forcing. Slow varying changes in the surface conditions can in turn alter the water mass formation and in turn the uptake capacity of heat and greenhouse gases by the ocean with cascading effects on ocean physics, biogeochemistry and ecosystems.

Consequences of the changes in water mass formation are changes in interior stratification of the ocean. Such changes have an impact on biogeochemical processes such as productivity or the extent of oxygen minimum zones.

3.2.2 Biogeochemical

The ocean is a key element in the global carbon and nitrogen cycles. Observed changes in the atmospheric concentrations of major greenhouse gases (e.g. CO_2, CH_4, and N_2O) result from the dynamic balance between anthropogenic emissions and the perturbation of natural processes that leads to a partial removal of these gases from the atmosphere. The ocean, as a carbon sink, has absorbed about half of historical anthropogenic carbon emissions, significantly damping climate warming in the atmosphere. As a result, however, the ocean has become about 30% more acidic since the start of the industrial revolution, with demonstrated but complex consequences for ocean ecosystems.

In response to the needs of the UNFCCC for systematic observation of the climate system, requirements for measurement of ocean carbon and biogeochemistry variables have been established by the Global Climate Observing System (GCOS) under direct guidance of the International Ocean Carbon Coordination Project (IOCCP) and in close collaboration with relevant observing networks. The Global Ocean Observing System (GOOS) Biogeochemistry Panel, guided by the Framework for Ocean Observing (FOO) and led by the IOCCP, identified three overarching requirements for sustained global observations with respect to ocean carbon and biogeochemistry:

1. the role of ocean biogeochemistry in climate
2. human impacts on ocean biogeochemistry
3. ocean ecosystem health

While requirements related to ocean carbon and biogeochemistry observations are, in general, relatively mature today, there remains a need to streamline specific aspects, especially ocean acidification-related requirements, in order to better support the Convention on Biological Diversity and the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES). The International Panel on Climate Change (IPCC) Workshop on Impacts of Ocean Acidification on Marine Biology and Ecosystems (2011, p. 37) has defined ocean acidification as “a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean.”

The need for coordinated information-gathering on ocean acidification and its implications for the overall ecosystem health (status) of the planet are widely recognized and endorsed by the United Nations General Assembly[1] and many other governmental and non-governmental bodies. There is a scientific need for global and long-term data to improve understanding of relevant chemical and biological processes; to assist in the design and interpretation of relevant chemical and biological processes; and thereby to improve predictive skills. The policy need is driven by the requirement for robust evidence on ocean acidification and its impacts, to provide scientific advice for appropriate management response at both national and international levels.

In response to both the scientific and policy needs, the scientific community developed the Global Ocean Acidification Observing Network (GOA-ON; www.goa-on.org) whose requirements and governance plan provide both broad concepts and critical details on how to achieve the three goals of GOA-ON: (i) improve our understanding of global ocean acidification conditions, (ii) improve our understanding of ecosystem responses to ocean acidification, (iii) acquire and exchange the data and knowledge necessary to optimize modelling of ocean acidification and its impacts. Coordinated, sustained ocean acidification observations have many specific applications within many societal benefit areas such as:

- carbon emission and other international policies
- socio-economic, cultural and potential fisheries impact forecasts
- coral reefs and livelihood

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[1] Paragraph 153 of Resolution 68/70, passed 9 December 2013: “… encouraged States and competent international organizations and other relevant institutions, individually and in cooperation, to urgently pursue further research on ocean acidification, especially programmes of observation and measurement…”

- international food and economic security
- shellfish aquaculture adaptation strategies
- tourism as related to coral reef and marine habitat degradation

The IPCC AR5 identified seven distinct oceanic sub-regions within the Atlantic basin. All of them are characterized by substantially different biogeochemical phenomena operating on a wide range of spatio-temporal scales, thereby challenging the design and implementation of a sustained, basin-wide Atlantic Ocean observing system that will meet the relevant societal and scientific requirements. The three overarching requirements drafted by the GOOS Biogeochemistry Panel are each divided into two main scientific questions described in the context of observing, understanding and predicting the biogeochemical phenomena influencing the Atlantic Ocean climate and ecosystem dynamics.

1. The role of ocean biogeochemistry in climate

The oceans play a critical role in the cycling of many greenhouse gases. Most notably the ocean is responsible for taking up and storing about 50% of the anthropogenic emissions of carbon dioxide since the pre-industrial era, thereby buffering (or mitigating) the rate of climate change.

Key Questions:

- How is the ocean carbon content changing?

As the Ocean is the biggest mobile reservoir of carbon in the Earth system, any change in its ability to take up and store anthropogenic carbon will have a direct impact on rates of atmospheric CO_2 concentrations, and hence on climate. Therefore, an observing framework that allows quantification and detection of change of both anthropogenic and total ocean carbon storage and uptake is critical (e.g. for setting emission targets, carbon accounting, model predictions, etc.). Additionally, understanding ocean oxygen and transient tracer fluxes and inventories are important indicators of ocean ventilation and respiration, which are needed for more accurate carbon budgets. In the high-latitudes of the Atlantic Ocean, the challenge is to distinguish the anthropogenic climate change-driven signal from the strong seasonal to decadal variability in primary and export production, regulated among other factors by spatially-heterogeneous shifts in the phenology and biological species composition of the spring phytoplankton bloom. Anthropogenic carbon storage and uptake regulated by the strength of ventilation is another key mechanism in the Atlantic that requires high frequency monitoring and improved model predictability.

- How does the ocean influence cycles of non-CO_2 greenhouse gases?

The ocean is the key unknown in the cycling of many non-CO_2 greenhouse gases, such as ozone depleting halocarbons (e.g. methyl bromide, bromoform etc.), CH_4, N_2O, and dimethyl sulfate (DMS). Upwelling associated with the eastern boundary current regions in the Atlantic is a large source of N_2O to the atmosphere. Oceanic production of N_2O is also enhanced under low oxygen conditions, found in the Eastern Tropical North Atlantic. Ocean measurements are essential for closing the budgets of the non-CO_2 greenhouse gases, which are potentially strong amplifiers of climate change. Furthermore, an ocean observing system that allows for early detection would serve as a warning system alerting the society to the risk of passing key tipping points in the climate system.

2. Human impacts on ocean biogeochemistry

Human activities like fossil fuel burning and industrial fertilizer production have perturbed the global elemental cycles of carbon and nitrogen and significantly impact ocean chemistry. For example, shifts in the carbon chemistry of seawater have been widely recorded, as well as changes in nitrogen and oxygen in both coastal and open ocean waters. These induce a variety of shifts and feedbacks in marine resources, which we still do not understand the full impact of. The rates at which these changes occur often exceed the recent geological record, and highlight the need for a more comprehensive, multivariable approach to ocean biogeochemical analyses in order to better track and predict changes and impacts on marine ecosystems.

Key Questions:

- How large are the ocean's "dead zones" and how fast are they changing?

While the oxygen content has increased in the North Atlantic due to greater mixing and ventilation driven by strengthening wind systems, it generally decreases in the upper layers of many areas of the Atlantic. Apart from the eutrophication driven hypoxia in the regional seas, there is a pronounced oxygen minimum zone (OMZ) in the Eastern Tropical North Atlantic and in the Gulf of Mexico, the extent of which is changing likely due to combined effects of altered circulation and rates of biological oxygen consumption. Low oxygen concentration leads to significant changes in biogeochemistry, such as reduction of available nitrate, which can impact ocean productivity and reduce diversity of local marine life.

- What are the rates and impacts of ocean acidification?

Ocean acidification will likely have significant effects on all levels of the trophic chain (e.g. reproduction, ecosystem structure, physiology) directly impacting future food security. Changes and impacts are expected to be heterogeneous and more severe in the coastal ocean. Due to different hydrographic properties of the water masses, pH and the solubility of aragonite and calcite (two calcium carbonate minerals) are naturally lower at high latitudes and in upwelling areas (e.g., Atlantic eastern boundary currents), where organisms and ecosystems (e.g. cold-water coral reefs) may be relatively more exposed to ocean acidification as a result. Additionally, the ability to observe and project the future regionally-varying rates of change in pH will be critical for the development of shellfish aquaculture adaptation strategies and the coral reef related tourism sector.

3. Ocean ecosystem health

Changes in ocean chemistry will directly impact the health of marine ecosystems, and in consequence, affect humans that rely on marine resources for ecosystem services (e.g. food security, aquaculture).

Key Questions:

- Is the biomass of the ocean changing?

The North Atlantic is one of the most intensively fished ocean basins. The major areas for harvesting marine living resources span the eastern North American, European, and Icelandic shelves. Quantifying the magnitude of changes in ocean biomass and productivity, and separating natural variability and secular trends is crucial for understanding and mitigating future impacts on fisheries. Changes in nutrient supply and distribution of macro- and micronutrients are key drivers of primary productivity, which will be impacted by changes in the nitrogen cycle (e.g. N_2 fixation, denitrification). In the North Atlantic subtropical gyre, there is high confidence that changes that reduce the vertical transport of nutrients into the euphotic zone (e.g. decreased wind speed, increasing surface temperatures, and stratification) will continue to reduce the rate of primary productivity and hence fisheries, thus expanding the world's most unproductive waters.

- How does eutrophication and pollution impact ocean productivity and water quality?

Land-based sources of nutrients (macro and micro) and carbon (organic and inorganic) into the coastal ocean increasingly lead to eutrophication and hypoxia directly impacting productivity and leading to deleterious effects such as harmful algal blooms (HABs), occurring both on the eastern and western side of the Atlantic basin. Furthermore, human pollution (persistent organic pollutants, plastics, dioxins) can adversely impact ecosystem health. It is important to make effective links between coastal and open ocean Atlantic observing systems in order to improve our understanding of both natural and anthropogenic variability in the biogeochemical drivers, and thereby to mitigate against these hazards.

3.3 Atlantic Knowledge Challenges – Biodiversity and Ecosystems

3.3.1 Overview

There are a range of knowledge challenges for the management of ocean health in the North Atlantic. Creating a prioritised synthesis is a challenge, especially when consulting with the scientific community, where each operator will be convinced that their area is crucial to the knowledge base for the conservation of biodiversity and the ecosystem approach to management of marine activities. The challenge is further increased by the differing approaches taken for assessment by the fisheries and conservation managers (Rice and Legacè, 2007; Rice, 2009). These differences are slowly being reconciled (Hilborn 2007, Worm et al. 2009). The OSPAR Science Agenda[2], published in 2015, lists 66 priority science needs to deliver the OSPAR North East Atlantic Environment Strategy. The ICES strategic plan for 2014-2018[3] expands on three goals that are pertinent to the knowledge challenges:

1. Develop an integrated, interdisciplinary understanding of the structure, dynamics, and the resilience and response of marine ecosystems to change
2. Understand the relationship between human activities and marine ecosystems, estimate pressures and impacts, and develop science-based, sustainable pathways
3. Evaluate and advise on options for the sustainable use and protection of marine ecosystems

Delivering the knowledge for the implementation of the MSFD is high on the agenda for both organisations and in addition the CFP is very influential on ICES. Both international organisations have non-EU member countries/contracting parties which also require knowledge for management under the ecosystem approach and conservation of biodiversity (Ramírez-Monsalve et al., 2016).

The ecosystem approach is fundamentally about the management of human activities. There are a huge number of documents and versions of the principles of the ecosystem approach (see Long et al., 2015; Dunstan et al 2016). Jake Rice (2011) sums them up as four components: take account of environmental forcing, create accountability for full footprint of activities, make governance broadly inclusive, and use integrated management. Both the OSPAR science agenda and the ICES strategic plan are attempts to increase the knowledge base to address these four components.

These knowledge challenges can be synthesised into the following broad categories:

- Methods for developing indicators and targets for biodiversity
- Techniques for assessment that account for differences in scale and resolution of monitoring and management
- Carrying capacity, ecosystem tipping points & ocean stressors
- Cumulative effects
- Analysis of social and economic consequences of management actions
- Maintaining the legitimacy and credibility of science for evidence based policy

The last two are outside the remit of AtlantOS and whilst crucial to the conservation of biodiversity and the ecosystem approach to the management of marine activities, they will not be further explored here.

Techniques for assessment that account for differences in scale and resolution of monitoring and management

There is a great challenge in reconciling the scales and resolutions of monitoring and assessments with the scales and resolution of management actions.

"Environmental assessments address different information needs at different levels and spatial scales, from relatively small spatial scales and low levels of integration to inform on suitable management measures, up

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[2] http://www.ospar.org/documents?v=7358

[3] http://www.ices.dk/explore-us/what-we-do/Documents/ICES_Strategic_Plan_2014_2018.pdf

to assessments at the level of (sub)-regional seas to follow policy implementation. Assessment scales should be defined taking into account both ecological considerations such as hydrodynamic and physical-chemical characteristics and biogeography, as well as management perspectives: provide a robust and adequate assessment of environmental state, enable the identification and evaluation of management measures. Spatial assessment scales will be different, depending on the issue, ranging from small scales in the case of local pressures or specific habitats to (sub)-regional or larger scales in the case of wide-spread pressures or species with a large distributional range.” (Prins et al., 2014)

There are examples of approaches (e.g. that of HELCOM with hierarchical nesting in the Baltic Sea) but much work is required to reconcile scale and resolution for monitoring, assessment and management action.

Carrying capacity, ecosystem tipping points and ocean stressors

Knowledge about the carrying capacity of the marine ecosystem is clearly vital when considering management actions, and also any likely impact of marine protected areas. Building this knowledge base is important for fisheries and aquaculture, for ensuring habitat and foodweb functioning and the impact of blue growth. Associated with this are tipping points and hysteresis. Ecosystem tipping points, or dramatic shifts in structure and function are often costly and hard to reverse (Selkoe et al 2015). Linked to the need to study tipping points is the need to uncover empirical indicators of the proximity to such critical thresholds (Scheffer et al., 2012). Further science is required to summarise the status of ecosystem components, with screening and prioritizing potential risks, and evaluating alternative management strategies (Levin and Möllmann 2015). However, advances in statistical, analytical and simulation modelling are needed before IEAs can robustly inform tactical management in systems characterized by regime shifts.

Cumulative effects

Interactions between multiple ecosystem stressors are expected to challenge biological processes, functions and biodiversity (Côté et al., 2016). Scientists are suggesting that stressor interactions are a key issue for conservation and management. This has been supported by OSPAR, in their science agenda and overall strategy. Cumulative effects analysis can be defined as a “*procedure for identifying and evaluating the significance of effects from multiple sources/activities and for providing an estimate on the overall expected impact to inform management measures. The analysis of the causes (source of pressures and effects), pathways and consequences of these effects on receptors is an essential and integral part of the process*” (Judd et al., 2015). This is clearly linked to the ecosystem tipping points and ocean stressors described above.

The follow on from improved knowledge on cumulative effects of pressures is better insight for trade-off analysis, i.e. the provision of knowledge to explore the trade-offs between different management actions. The provision of tools for trade-off analysis is thought to be severely lacking when considering ecosystem services (Mach et al., 2015). An example of such a trade-off analysis is that by Jennings et al., (2012) where the landings value of fisheries, the habitat sensitivity, and the impact of fishing on those habitats are compared.

3.3.2 The validity of the Framework approach for ocean health

The approach of defining global or basin-scale phenomena and Essential Ocean Variables applied to the biology of the ocean, its ecosystems, their ecosystem services, and the related human pressures on ecosystems is new, and faces a number of challenges.

The complexity of phenomena and interactions between particular ocean ecosystems, between trophic levels, different habitats and species, and in the human influence on these variables is arguably far higher than for the biogeochemistry and physics of the ocean. The range of ocean ecosystem services provided by the ocean, and therefore the potential societal benefits in monitoring these ecosystem services and the pressures on them for ecosystem-based management is also high. These include for example provisioning services like fish for food, tourism related to coral reefs, local livelihoods, and even cultural value of iconic species.

Several basic facts might argue for a more modular, regional approach than the definition of universal biological/ecological Essential Ocean Variables:

- the number of different ocean ecosystems is high, and they are geographically differentiated;
- the human pressures and impact on ocean ecosystems is often very localized and geographically heterogeneous;
- many of the existing regulatory regimes, balancing human activities and environmental stewardship, and therefore which require sustained monitoring of ocean biology or ecosystems, are regional;
- sustained monitoring observing technology is generally at a low readiness level for basin-wide implementation; and
- generally pragmatic ecosystem-based management is a 'wicked problem' requiring stakeholder agreement and complex judgment, trade-offs between human and ecological goals, local and global scales, and is often lacking in clear objective measures.

These facts have led ICES to a regional approach to defining the key ecosystems under threat and the key human drivers of impact on those ecosystems, and therefore a regional approach around Europe to the definition of the key indicators for reporting under various requirements, including the EU Marine Strategy Framework Directive. Many of these indicators are related to the human activity that can be a driver of impact on ocean ecosystems, rather than on ocean ecosystem state itself.

On the other hand, two factors argue nevertheless for an attempt at defining the globally and Atlantic-wide key biological and ecological Essential Ocean Variables.

The first is that there is increasing scientific understanding that human drivers of impact on ocean ecosystems are multiple, and that they do not add up linearly. The complexity of interactions in ocean ecosystems mean that they are nonlinear systems, and can have thresholds and other surprising behaviour in the face of multiple pressures, including climate change (temperature increases, acidification, deoxygenation), local pressure from fisheries, resource extraction, pollution, and other human activity. This is an argument that direct sustained observation of ocean ecosystem state is important to identify these thresholds or surprises in the behaviour of ocean ecosystems under human impact. Growing demand to not only monitor the present state but also to forecast its future state again calls for the basic sustained observations needed to improve predictive models.

The second is that there are increasing regulatory and other requirements for basin-wide and global assessments of the ocean, including ocean ecosystem state and services. While taking into account the regional distribution of ocean ecosystems, there are still nevertheless a number of key ocean biological variables that might be considered universal over large areas of the Atlantic, in which it will be important to have harmonized and inter-comparable data from a maximum number of sites, in order to contribute to these assessments and feed Atlantic-wide and global policy for ecosystem-based management of ocean resources.

It is the scientific and policy users of ocean ecosystems information for both of these reasons defined above that need to be well-defined in order to have a rational set of requirements.

Once requirements set, activity should not only focus on the implementation of sustained observations, but also in the development of interoperable data systems and map-based visualization systems, and training and education to allow the creation of derived products and to expand the user base for these observations.

The initial set of biological and ecosystem EOVs identified here below are largely at a low readiness level, and will necessarily need to be supplemented at a regional level by observations of natural system variables and human pressures that are of greatest local priority, and given local capacity, technology, and development for observations.

4 Essential Ocean Variables

Essential Ocean Variables (EOVs) are the *Framework for Ocean Observing* concept of the fundamental physical, biogeochemical, and biological measurements needed for the scientific understanding of ocean phenomena and the provision of applications in support of Societal Benefits. Essential means that these observables are the minimum subset required; they are not replaceable by other variables. Their essential nature is defined by both:

- a high feasibility of sustained observation, based on the platforms and sensors that can observe this variable at the space and time scales and accuracy needed to capture the required phenomena, and
- a high impact of the observation in creating the application or contributing to the needed scientfic knowledge, and therefore providing the societal benefit.

EOVs are basic variables observable by one or more practical instrumentation systems. A suite of EOVs is necessary to provide the data to derive higher level indicators or phenomena in support of scientific research and addressing societal issues related to the ocean and climate; each phenomena or indicator requires a coordinated set of EOVs. Each EOV, in turn, is supported by a variety of platforms or Observing Elements capable of producing data for that EOV. Many EOVs are also identified by GCOS as Essential Climate Variables.

EOV Specification Sheets, part of the GOOS Strategic Map linking EOVs to societal benefits, describe each of these EOVs: their importance in scientific phenomena, present observation strategies (e.g., spatial and temporal resolution, accuracy, technological readiness level), required complementary variables, derived variables, and the observation programmes and networks measuring the data.

The early 2016 release of the physical and biogeochemical EOV specification sheets is available at goosocean.org/eov,

Specification sheets for the biology and ecosystem EOVs will be released in late 2016, reflecting their lesser state of maturity and readiness.

The link between the generic ocean phenomena to capture and EOVs is illustrated in the table below:

	Sea Surface Temperature (SST)	Subsurface Temperature	Sea Surface Salinity (SSS)	Subsurface Salinity	Surface Current	Subsurface Currents	Sea Surface Height (SSH)	Sea State	Sea Ice	Ocean Surface Stress	Ocean Surface Heat Flux	Oxygen	Inorganic Macro Nutrients	Carbonate system	Transient tracers	Suspended Particulates	Nitrous oxide	Carbon Isotopes	Dissolved Organic Carbon	Phytoplankton	HAB	Zooplankton	Status Fish	Apex Predators	Coral Cover	Seagrass Cover	Mangrove Cover	Macroalgal cover	Microbes	Salt Marsh area	Tags/tracking
Extreme Events	-	-	-	-	X	-	X		-	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sea Level	-	X	-	X	-	-	X	-	-	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Circulation	X	X	-	X	X	X	X	-	-	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fronts / Eddies	X	-	X	-	X	X	X	X	-	X	-																				
Tides	X	-	-	-	X	X	-	-	-	-	-																				
Near-inertial Oscillations	X	-	-	-	X	-	-	-	-	-	-																				
Heat Storage	-	X	-	X	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Air-sea fluxes	X	-	X	-	X	-	-	X	X	X	X	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mixed Layer	-	X	-	X	-	-	-	-	-	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Stratification	-	X	-	X	-	-	-	-	-	-	X																				
Upwelling	-	X	-	X	-	-	-	-	-	X	X	-	-	-	X	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-
Watermass	-	X	-	X	-	-	-	-	X	X	X																				
Riverine	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fresh Water Cycle	-	-	-	X	-	-	-	-	-	-	X																				
Surface Waves	X	-	-	-	X	-	-	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sea Ice Extent	-	-	-	-	-	-	-	-	X	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Coastal Processes	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ocean Acidification phenomena	-	-	-	-	-	-	-	-	-	-	-	X	-	X	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-
Ocean Carbon Cycle	-	-	-	-	-	X	-	-	-	-	-	X	-	X	-	-	-	X	X	-	-	-	-	-	-	-	-	-	-	-	-
non-CO2 greenhouse gas cycles	-	-	-	-	-	-	-	-	-	-	-	X	-	-	X	-	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-
Eutrophication hypoxia	-	X	-	X	-	-	-	-	-	-	-	X	-	X	-	X	-	-	X	X	-	-	X	X	-	-	-	X	-	-	-
Ocean productivity	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-	-	X	X	X	-	X	-	-	-	-	-	X	-	-	-
Particle concentrations	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	X	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-
Particulate Matter Transport	-	-	-	-	X	X	-	-	-	-	-	-	X	-	-	-	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-
Habitat modification	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	X	-	X	X	X	-	-	X	-
Food webs	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	X	X	X	-	X	-	X	X	-	X
Contaminants Sources/Transport	-	X	-	-	X	X	-	-	X	-	-	X	X	X	X	X	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-
Contaminant sinks / transformation	X	-	X	-	X	X	-	-	-	X	-	X	X	-	X	X	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-
Pollution Impacts	-	-	-	-	-	-	-	-	-	-	-	X	X	-	X	X	-	-	X	X	X	X	X	X	-	X	X	X	-	-	-

4.1 Readiness

Individual EOVs are at differing stages of maturity, with physical EOVs being the most firmly established. However, descriptions of even the most mature EOVs evolve with new observation technologies, measurement techniques and algorithms, and with improved understanding of the links between different EOVs (i.e., complementarity) and between EOVs and scientific phenomena.

Different approaches can be taken in defining EOVs, and in some cases, agreement on what constitutes an EOV has not yet been reached. In the case of ocean floor cover, for example, one philosophy defines floor cover as the EOV (with seagrass, coral, etc., being "values" of the variable or subvariables), while a different approach has seagrass, coral, and other types of floor cover each being an EOV. Work to reconcile these approaches, including the aggregation of subvariables within a small number of core EOVs, is ongoing.

Table: GOOS Essential Ocean Variables and readiness level as of May 2016

Physics	*Biogeochemical*	*Biology and Ecosystems*
Sea Surface Temperature (SST)*	Oxygen*	Phytoplankton* biomass and productivity
Subsurface Temperature *	Inorganic macro nutrients*	HAB incidence
Sea Surface Salinity (SSS)*	Carbonate system*	Zooplankton* diversity
Subsurface Salinity*	Transient tracers*	Fish abundance and distribution
Surface Currents*	Suspended particulates	Apex predator abundance and distribution
Subsurface Currents*	Nitrous oxide*	Live coral cover*
Sea Surface Height(SSH)*	Carbon isotope (^{13}C)	Seagrass cover*
Sea State*	Dissolved organic carbon	Mangrove cover*
Sea Ice*	Ocean colour*	Macroalgal canopy cover*
Ocean Surface stress*		Microbes
Ocean Surface Heat Flux*		
* also an Essential Climate Variable [sometimes aggregated] Concept Pilot Mature		

4.2 Overview of EOVs

High-level descriptions of each of the present EOVs demonstrate their importance to understanding ocean phenomena and providing applications for societal benefit; more detail is provided in the EOV Specification Sheets, noted above.

Sea Surface Temperature (SST)

SST exerts a major influence on the exchanges of energy, momentum and gases between the ocean and atmosphere. These heat exchanges are a main driver of global weather systems. The spatial patterns of SST reveal the structure of underlying ocean dynamics. SST is a complex quantity as it not only controls fluxes, but also responds to turbulent and radiative exchanges at the surface. The database of in-situ measurements currently extends back to the late 18th century; additional recovered and digitized historical measurements may be added. In the past 30 years, near-global sampling of SST has become available on a daily to weekly basis due to infrared radiometers on polar-orbiting and geosynchronous satellites and of microwave radiometers on polar-orbiting satellites. For climate applications, the accuracy requirements set by GCOS are very stringent, being an absolute accuracy of 0.1K, with stability at the level of 0.03K/decade, both over space scales of ~100-1000 km. The Group for High Resolution SST (GHRSST; www.ghrsst.org) is an international consortium of scientists and operational practitioners focused on SST derivation and applications.

Subsurface Temperature

Changes in subsurface temperature impact a variety of ocean services, including the growth rate of farmed fish as well as the distribution and abundance of wild fish stocks and other marine species of significant economic and social value. In addition, changes in subsurface temperature induce changes in mixed-layer depth, vertical and lateral ocean thermal / density stratification, mixing rates, and currents. All of these physical changes can affect marine biology directly and indirectly through changes in marine biogeochemistry, such as nutrient and oxygen recycling, uptake of (anthropogenic) carbon emissions, and ocean acidification. Subsurface observations are also important in validating satellite-derived SST data, and are used in many weather and climate applications, including data assimilation / forecasting and understanding ocean heat content, the global energy budget, and sea level change. While ocean subsurface temperature observations have a long recorded history, the quality and quantity of these measurements have dramatically improved since 1960 with technology, including moorings, gliders, drifters (e.g., the Argo program), and ship-based observations.

Sea Surface Salinity (SSS)

SSS is a key parameter for monitoring the global water cycle (evaporation, precipitation, and glacier and river runoff) and observations over large scales can be used to infer long-term changes in the hydrological cycle and to quantify the evolution of the ocean in response to climate change. Surface salinity, together with surface temperature and air-sea fluxes (heat and momentum (wind)) can be used to determine the evolution of the surface expression of fine to large-scale ocean frontal features and eddies which have a strong influence on the diversity and health of the ocean ecosystem. SSS is an important input in data assimilation ocean models used to provide gridded global estimates of ocean circulation at varying spatial and temporal scales. Surface salinity is measured over various spatial and temporal scales, from space by satellites and in-situ by water intake from research and commercial ships, autonomous floats and drifters, and surface gliders.

Subsurface Salinity

A global subsurface salinity observing system is vital to close the global hydrological cycle and understand the halosteric component of sea level change. Subsurface salinity, temperature, and velocity observations, are required to calculate in-situ density and ocean freshwater transports. In addition, changes in subsurface salinity induce changes in mixed-layer depth, vertical and lateral ocean density stratification, mixing rates, and currents. Subsurface observations are also important in validating satellite-derived SSS data, and are used in many weather and climate applications, including data assimilation / forecasting and understanding the global water cycle and sea level change. While ocean subsurface salinity observations have a long recorded history, the quality and quantity of these measurements have dramatically improved since 1960 with technology, including moorings, gliders, drifters (e.g., the Argo program), and ship-based observations.

Surface Currents

Surface currents transport significant amounts of heat, salt, passive tracers, and ocean pollutants. On basin scales, zonal surface currents and their variations are key in climate to weather fluctuations. Wind stress and heat flux depend upon the speed of the near-surface wind relative to the moving ocean surface, which can be significantly affected by surface currents such as the western boundary currents, and at smaller scales by mesoscale variability. Convergences/divergences, spiralling eddies, and filaments all contribute to vertical motion and mass exchange. Surface currents impact the steepness of surface waves, important for accurate marine sea state forecasts. Because of their significance in advecting passive particles, surface current data are also important for applications such as oil spill and marine debris response, search and rescue operations, and ship routing. Currents, particularly tidal currents, can also modify storm surge impacts and sea level changes. The existing observing system captures much of the spatial and temporal scale of surface currents, from basin-wide currents to submesoscale and turbulent scales. Moorings and land-based HF-radars are local and frequent, but limited in coverage. Lagrangian drifting buoys and satellite altimeter derived surface geostrophic currents are global, though drifters are sparsely distributed.

Subsurface Currents

Observations of subsurface ocean velocity are needed to estimate oceanic transport of mass, heat, freshwater, and other properties on local to global scales, and are particularly important in resolving the complex velocity structure of the major boundary currents, at the sea floor, near the equator, in ocean eddies, and in waves. Currents are used in data assimilation models to provide gridded global estimates of ocean circulation and global mean and eddy kinetic energy. Velocity profile information is also used to roughly estimate ocean mixing using fine-scale parameterizations of turbulent dissipation by internal wave breaking. Subsurface currents are measured directly or inferred from temperature, salinity and pressure data using the geostrophic approximation; in the latter case, the shear can be determined, but not the absolute velocity field, which is needed for accurate transport estimates. This is primarily an issue in the open ocean, as boundary, equatorial currents, and other constrained intense currents are observed directly using moored Acoustic Doppler Current Profilers (ADCPs) at hourly time resolutions. Gliders, using similar techniques, are beginning to be used to monitor boundary currents and ocean eddies. Shipboard Acoustic

Doppler Current Profilers (SADCP) and Lowered ADCP (LADCP) provide subsurface current data from boundary current scale to basin scale depending on horizontal resolutions and tracks of research voyages.

Sea Level or Sea Surface Height (SSH)

Sea level has been identified as one of the primary indicator of global climate change; global mean sea level change provides a measure of the net change in ocean mass due to melting of glaciers and ice sheets and the net change in ocean volume due to thermal expansion. At the coast, high frequency meteorological forcing on time scales of hours to days can drive significant departures of SSH from the harmonic tide with consequences for inundation and navigation. Sea level change observations contribute vital information to characterizing intra-seasonal variably such as ENSO, and the correlation between sea surface height (SSH) variability and the underlying subsurface temperature anomalies can be exploited to derive analyses of the upper ocean heat content and derived products such as Tropical Cyclone Heat Potential. Regional and coastal changes in sea level, far larger than global averages, result from several factors, including changes in temperature, salinity and near surface winds. Coastal measurements of sea level, of extreme relevance for societal impacts, are under-sampled by current altimeters, but planned missions, including SWOT, should improve small-scale measurements. In situ Global Sea Level Observing System (GLOSS) provide calibration and validation data to complement satellite observations.

Sea State

Waves are generated by ocean surface vector stress and modified by bathymetry and surface currents. Sea state impacts marine safety, marine transport, and may damage marine structures. Waves affect air/sea exchanges of momentum, moisture, and CO_2, and also impacts beach erosion, storm-related water damage, surface albedo, the transport of larva and contaminants such as oil, and the growth and decay of sea ice. Primary measurements are wave height (usually significant wave height (SWH), but sometimes maximum wave height), wave period (and hence wavelength) and wave direction (from a much more limited set of platforms). 1-D spectra are measured by most moored buoys; a limited number of directional wave spectra are measured from moored buoys, wave radars, and bottom mounted pressure arrays (in shallow water). Parameters of interest not measured include crest height (usually parameterized from wave spectra or SWH), wave breaking, whitecap coverage (derived from some satellite estimates), rogue waves, and Stokes drift.

Sea Ice

Energy budgets are heavily impacted by the formation / melting of ice (latent heat) and the presence / absence of ice cover (albedo, evaporation); ice plays a very large role in determining the sign of the local energy balance. In addition, the formation and melting of ice modifies the salinity of the surface water, altering stratification and local circulation, and the change in roughness between ice and water impacts differential stress, and hence is related to relatively strong vertical motions and transports near the ice edge. Primary parameters for sea ice are: concentration / extent / area, motion, seasonality, age and thickness. Snow cover thickness is also a crucial parameter, particularly for accurate retrieval of ice thickness for most remote observation methods and because snow contributes to sea ice mass through snow ice formation and greatly affects ice growth and melt rates due to its high albedo and thermal insulation properties. On-ice in situ observations and subsurface observations are currently very sparse; but several efforts aim to improve subsurface observations. Satellites are important tools in providing measurements of sea ice extent, and high-resolution sea ice analysis (e.g., ice thickness and deformation) use synthetic aperture radar (SAR) data.

Ocean Surface stress

Stress, the rate at which horizontal momentum is transferred from the atmosphere to the ocean, influences the air/sea exchange of energy (sensible and latent heat), water (evaporation) and carbon (CO2) and is critically important for determining large scale ocean currents and transport, (coastal and open ocean) upwelling and downwelling (including mixed layer evolution and deep water formation), primary productivity, and cross shelf transport. Surface stress is now measured from satellites in addition to buoys, ships, and other ocean platforms. Since ocean surface stress changes rapidly in both time and space, the sampling density and relatively good accuracy of satellites make them particularly useful. In-situ observations have improved in robustness and accuracy in the last decade, and can now be deployed on buoys for multiple seasons. Observations from ships are also available, but like the buoy observations have very limited coverage in space and time. Stress has traditionally been estimated through 'bulk formulas' and observations of SST, near surface air temperature and humidity, surface vector winds, and surface pressure.

OceanSurface Heat Flux

The fluxes of latent heat (due to evaporation) and sensible heat (due to differences in air-sea temperatures) are major contributors to the energy budget, and are largely responsible for thermodynamic coupling of the ocean and atmosphere at global and regional scales. Latent heat flux is proportional to evaporation, a key component in the global hydrological cycle. Variations in these fluxes leads to largescale variability in weather (climate) patterns; they are sensitive indicators of changes in climate, including floods and droughts, storm tracks and intensity and, on longer time scales, El-Nino and other climate cycles, each of which impact regional populations, economies, and infrastructure. For example, improved predictions of ENSO phase and associated impact on regional weather patterns could be extremely useful to the agricultural community. Sensible and latent heat fluxes have traditionally been estimated through 'bulk formulas' and observations of SST, near surface air temperature and humidity, surface vector winds, and surface pressure, including recently from satellites. Fluxes can also be measure directly from buoys, ships, and other ocean platforms.

Dissolved Oxygen (O_2)

Measuring and understanding the large (mostly) decreasing trends in the concentrations of dissolved oxygen in the ocean over the last few decades have important implications for our understanding of anthropogenic climate change. Sub-surface oxygen concentrations in the ocean everywhere reflect a balance between supply through circulation and ventilation and consumption by respiratory processes. An Atlantic observing network of O_2 among other things results in the following products: (i) improved constraint on the ocean-land-partitioning of anthropogenic carbon dioxide (CO_2), (ii) determination of the seasonal to interannual net remineralization rates as a proxy for the amount of organic matter exported from the surface ocean, (iii) better interpretation of variations in water mass ventilation strength, (iv) increased availability of crucial data (initial conditions, evaluation) for ocean biogeochemistry models. O_2 sensors are currently deployed in almost every available observing platform (Appendix, Table 5.1.1.), most of which have a mature technology readiness level.

Inorganic Macronutrients

The availability of inorganic macronutrients (nitrate (NO_3), phosphate (PO_4), silicon (Si), ammonium (NH_4), nitrogen dioxide (NO_2)) in the upper ocean frequently limits and regulates the amount of organic carbon fixed by phytoplankton, thereby constituting a key control mechanism of carbon and biogeochemical cycling. There is a number of biogeographic regions in the open ocean Atlantic characterized by different macronutrient regimes, either permanently or seasonally limiting the growth of phytoplankton. Measuring changes in macronutrient concentrations is essential to constraining net biological production and export fluxes, detecting shifts in biogeographic regimes, but also monitoring eutrophication and pollution phenomena.

Carbonate System

The observations required to constrain the carbon system at a point in space and time are any two of dissolved inorganic carbon (DIC), total alkalinity, partial pressure of carbon dioxide (pCO_2) and pH, and associated physical variables (temperature and salinity). High resolution and long-term observations of the carbonate system are essential for distinguishing the climate change-driven trends from the strong seasonal to decadal variability signal in net biological production and export flux, in particular in the high-latitude spring bloom systems. The carbon system is in a delicate balance such that high quality observations and predictions of the carbonate system will continue to be required to have a mechanistic understanding and ability to predict the changes in the Atlantic anthropogenic carbon flux and storage in the interior ocean, and ocean acidification rates.

Transient Tracers

Transient tracers are a group of (chemical) compounds that can be used in the ocean to quantify ventilation strength, transit time distribution and transport time-scales. These compounds are all conservative in sea-water, or have well-defined decay-functions, and a well-established source function over time at the ocean surface. Measurement of transient tracers in the interior ocean thus provides information on the time-scales since the ocean was ventilated, i.e. in contact with the atmosphere. Knowledge of the transit time distribution of a water-mass allows for inference of the concentrations or fates of other transient compounds, such as anthropogenic carbon or nitrous oxide. Commonly measured transient tracers are the chlorofluorocarbons (CFCs) 11 and 12, although in the past also CFC-113 and CCl_4 have been measured. More recently, measurement of transient tracers includes sulphur hexafluoride (SF_6), radioactive isotopes 14C, tritium (decaying to stable 3He), and argon isotope 39Ar.

Suspended Particulates

Suspended particulates include the variables referred to as Particulate Organic Matter (POM), i.e. Particulate Organic Carbon (POC) and Particulate Organic Nitrogen (PON); but also particulate inorganic carbon (PIC) and biogenic silica (BSi); as well as the vertical transport (export) flux of all particulates. Observation of POM within a global observing system would directly address the question of whether the ocean’s biomass and productivity are changing. Changes in POM could be important indicators of deteriorating water quality due to eutrophication in coastal regions, and of declines in primary production that could potentially translate up the food chain negatively impacting fisheries. Observation of PIC would directly address the question of what impacts ocean acidification has on calcareous organisms and thus community structure. Export production gradients occur over a multitude of spatial and temporal scales, therefore high spatial resolution measurements are needed, for example in upwelling areas in the Atlantic eastern boundary currents, while high temporal resolution measurements are needed in particular in polar regions where spring blooms can be highly pulsed and the bulk of annual export rates occur often over only a few weeks of time.

Nitrous Oxide (N_2O)

The oceans - including its coastal areas such as continental shelves, estuaries and upwelling areas - are a major source of N_2O and contribute about 30% to the atmospheric budget of this important climate-relevant trace gas. Because of the on-going decline of chlorofluorocarbons and the continuous increase of N_2O in the atmosphere, the contributions of N_2O to both the greenhouse effect and ozone depletion will be even more pronounced in the 21st century. An Atlantic ship-based observing network of N_2O not only helps estimate global N_2O emissions but also helps capture information about such ocean phenomena as deoxygenation, eutrophication and upwelling.

Stable Carbon Isotopes

Recent improvements in measuring the carbon-13 to carbon-12 isotope ratio (13C/12C) and concentration of carbon dioxide (CO_2) gas dissolved in seawater using field portable spectrometers open up the possibility of underway 13C/12C observations across large portions of the surface ocean. Such data sets would substantially improve δ13C-based estimates of organic matter export rate and of the air-sea $13CO_2$ flux. The latter term can be compared to depth-integrated $13CO_2$ inventory changes in the water column to provide a separation of anthropogenic CO_2 change due to air-sea CO_2 flux versus change due physical transport by ocean circulation. Recent application of this approach in the North Atlantic indicates that 50% of the anthropogenic CO_2 increase in this ocean basin is a result of transport from the South Atlantic as part of the Meridional Overturning Circulation.

Dissolved Organic Carbon

Dissolved organic carbon (DOC) exceeds the inventory of organic particles in the oceans by 200 fold, making it one of the largest of the bioreactive pools of carbon in the ocean, second only to dissolved inorganic carbon. The size of the reservoir (comparable to that of atmospheric carbon dioxide (CO_2)), as well as its role as a sink for autotrophically fixed carbon, as a substrate to heterotrophic microbes, and as a sink/source of carbon involved in climate variations over long time scales, highlights its importance in the ocean carbon and nitrogen cycles. DOC exported from the epipelagic zone contributes around 20% to the biological pump via Meridional Overturning Circulation.

4.3 Biological and Ecosystem EOVs

A divergence of approaches remains to global, regional, and thematic approaches to the identification of the essential biological and ecosystem variables to measure, as mentioned in Section 3.3.2. These include the approaches taken by the GOOS Biology and Ecosystems Panel and GEO BON at the global level, the different GOOS Regional Alliances, and the European MSFD and other conventions.

Over the course of the AtlantOS project, a specific workshop will focus on the harmonization and inter-comparability of the outputs of the different approaches, building towards a more common system. The ongoing global and regional activities on observing requirements will also be tapped to provide the updated requirements report towards the end of the project.

4.3.1 GOOS Biology and Ecosystems Panel Approach

Continuing with their DPSIR approach (see Section 2.3.1), the GOOS Biology and Ecosystems Panel has conducted a survey of more than 50 different regional and global observing programmes to evaluate the current state of biological and ecosystem observations, identify pathways to aggregate networks, demonstrate the befits gained from integrated datasets, and identify the feasibility and impact of sustained observation of biology and ecosystem variables. Early results from the survey identified the candidate EOVs shown in the Table in Section 4.1, with most identified as being only in the concept stage for basin-scale sustained observations.

Two EOVs, Zooplankton diversity and Live coral cover were identified as being in the pilot stage, with a higher readiness level for basin-scale sustained observing networks to be established. Zooplankton diversity measured by Continuous Plankton Recorder surveys have a particularly long history in the North Atlantic Ocean, with surveys of the North Atlantic carried out in essentially unchanged fashion since the 1940s.

Work in the definition of this common set of biology and ecosystem EOVs applicable globally across GOOS continues.

4.3.2 Core set of indices for MSFD and other European conventions

There are different ways to categorise marine environmental indicator development in Europe. Those already agreed through a political/governance process (top down) and those being developed and explored by scientists, with the intention of having those indices brought into a governance process (bottom up). Below, three politically agreed approaches are described; for EU national water (the MSFD), for all waters of the north east Atlantic (national and international, OSPAR) and those of the Baltic (HELCOM). The MSFD provides an overarching umbrella of objectives for good environmental status of the marine environment which European member states should deliver by 2020. Many member states have agreed to use the regional sea commissions to deliver these objectives and thus the lists of indicators are tangible. These projects are developing new indicators with the intention for these indicators to be taken up by countries and regional seas commissions. Indicator development in the Mediterranean and Black Seas is still in its infancy.

EU Marine Strategy Framework Directive (MSFD)

The Marine Strategy Framework Directive aims to achieve Good Environmental Status (GES) of the EU's marine waters by 2020 and to protect the resource base upon which marine-related economic and social activities depend. It is the first EU legislative instrument related to the protection of marine biodiversity, as it contains the explicit regulatory objective that "biodiversity is maintained by 2020", as the cornerstone for achieving GES. The Directive enshrines in a legislative framework the ecosystem approach to the management of human activities having an impact on the marine environment, integrating the concepts of environmental protection and sustainable use. See http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm. The MSFD is applicable from coastal waters to the edge of the European EEZ.

The MSFD asks all member states to define good environmental status (GES) and then deliver it by 2020. It provides guidance but does not set or list indicators. It requires GES to be defined for 11 so called “descriptors”. Guidance is given as to which qualities of those descriptors should be considered, in what are called “criteria”. There are currently 29 criteria spread across the descriptors. The number of criteria is likely to change as the MSFD has just been reviewed and may be revised.

The 11 descriptors of the MSFD:

- Descriptor 1. Biodiversity is maintained
- Descriptor 2. Non-indigenous species do not adversely alter the ecosystem
- Descriptor 3. The population of commercial fish species is healthy
- Descriptor 4. Elements of food webs ensure long-term abundance and reproduction
- Descriptor 5. Eutrophication is minimised
- Descriptor 6. The sea floor integrity ensures functioning of the ecosystem
- Descriptor 7. Permanent alteration of hydrographical conditions does not adversely affect the ecosystem
- Descriptor 8. Concentrations of contaminants give no effects
- Descriptor 9. Contaminants in seafood are below safe levels
- Descriptor 10. Marine litter does not cause harm
- Descriptor 11. Introduction of energy (including noise) does not adversely affect the ecosystem

OSPAR

The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) is the legislative instrument regulating international cooperation on environmental protection in the North-East Atlantic. It is made up of 15 governments, and the European Commission. It has agreed OSPAR wide common indicators, and regional indicators (Annex 1). The OSPAR area covers the north east Atlantic from 36°N to 45°W. They also work in partnership with the North-East Atlantic Fisheries Commission (NEAFC), who manage fisheries in international waters. The list of common indicators is adapting as OSPAR prepares for the next round of the MSFD with their 2017 Intermediate Assessment on the state of the marine environment. OSPAR also has a long list of candidate indicators, which are being developed by researchers.

HELCOM

HELCOM (Baltic Marine Environment Protection Commission - Helsinki Commission) is the governing body of the Convention on the Protection of the Marine Environment of the Baltic Sea Area, known as the Helsinki Convention. HELCOM was established about four decades ago to protect the marine environment of the Baltic Sea from all sources of pollution through intergovernmental cooperation. Whilst the HELCOM area is not covered by the project AtlantOS, HELCOM are a useful example of the potential indicators that regional sea commission

The HELCOM has developed a set of core indicators for following up the effectiveness of the implementation of the Baltic Sea Action Plan. The core indicators will also support the EU Member States in the Baltic Sea region in implementing the EU Marine Strategy Framework Directive. The agreed list from 2014 is currently being reviewed for another assessment in 2018 (see Annex 2). The core indicators focus particularly biodiversity, eutrophication and hazardous substances in the Baltic Sea. HELCOM intends to have targets or boundaries for good environmental status that will enable classification of the environmental status into different status quality classes. HELCOM's main principles for the development of core indicators are that they will describe the status or pressures on the scale of the entire sea area, they have a scientific basis and that they reflect anthropogenic pressures and thus enable improvement of status by management measures on land or at sea. HELCOM has 41 biodiversity core indicators. http://www.helcom.fi/baltic-sea-trends/indicators/

5 Observing Elements: platforms and networks

In order to actually implement a sustained ocean observing system, the more theoretical ideas above about what to observe must be then concretely translated into a coordinated set of observing platforms with sensors measuring EOVs, deployed appropriately to capture the needed space and time scales and accuracy required for the applications identified.

The table below gives the next link in the GOOS Strategic Mapping, from EOV to observing platform.

	Satellites	HF Radar	Moorings	Boundary Current Arrays	Ice tethered profilers	Sea Level Gauges	Argo profilers	Deep Argo	Gliders	Surface gliders	Drifting buoys	Marine Meteorology	XBT and TSGs	Ships of Opportunity	Ship Based Time Series	Ship Based Sampling; Repeat Hydrography	Animal CTD	Acoustic Network	Coastal Surveys	Nets CPR	Particulate Export flux
Sea Surface Temperature (SST)	-	-	-	X	-	-	-	-	X	X	X	X	-	X	X	-	-	-	-	-	-
Subsurface Temperature	-	-	X	X	X	-	X	X	X	-	-	X	X	-	X	X	X	-	-	-	-
Sea Surface Salinity (SSS)	X	-	X	X	-	-	-	-	-	X	X	X	-	X	X	X	-	-	-	-	-
Subsurface Salinity	-	-	X	X	X	-	X	X	X	-	-	X	X	-	X	X	X	-	-	-	-
Surface Current	X	X	X	-	-	-	-	-	-	X	X	X	-	X	-	-	-	-	-	-	-
Subsurface Currents	-	-	X	X	-	-	-	-	-	-	-	X	-	-	-	X	-	-	-	-	-
Sea Surface Height (SSH)	X	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sea State	X	-	-	X	-	-	-	-	-	X	-	-	-	X	-	-	-	-	-	-	-
Sea Ice	X	-	-	-	-	-	-	-	-	-	-	X	-	X	-	-	-	-	-	-	-
Ocean Surface Stress	X	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ocean Surface Heat Flux	X	-	X	-	-	-	-	-	-	X	-	-	-	-	X	-	-	-	-	-	-
Oxygen	-	-	-	-	-	-	X	-	X	-	-	X	-	-	X	X	-	-	-	-	-
Inorganic Macro Nutrients	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-
Carbonate system	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-
Transient tracers	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-
Suspended Particulates	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-	-	-	X
Nitrous oxide	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-
Carbon Isotopes	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	X
Dissolved Organic Carbon	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-
Phytoplankton	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-	-	X	X
HAB	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-
Zooplankton	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-	-	X	-
Status Fish	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Apex Predators	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	X	X	-	-	-
Coral Cover	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-
Seagrass Cover	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-
Mangrove Cover	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-
Macroalgal cover	X	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-
Microbes	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-
Salt Marsh area	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-
Tags/tracking	X	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	X	X	-	-	-

The requirements then need to be further distilled into the observing network targets for each type of platform and sensor in order to develop a detailed implementation plan, balancing feasibility and impact.

In the context of the AtlantOS project, these targets are a subject of additional work in WP1 using OSEs and OSSEs as well as analytical approaches, in WP5 for regional approaches, WP8 for specific applications, and are needed in WP9 to develop the monitoring tools describing the status of the AtlantOS system.

The identified observing platforms and networks below are the in situ platforms and networks (platform-based groups coordinating on a basin scale) that are capable of primarily measuring physical and biogeochemical EOVs. Like for biological and ecosystem EOVs, the platforms and networks focused on biology and ecosystems monitoring are still under identification and development.

Profiling floats

Profiling floats are battery-powered autonomous floats that spend most of their life drifting at depth, rising to the surface at typically 10-day intervals to measure vertical profiles of ocean properties and transmit the data to the satellites. Global (Argo, http://www.argo.ucsd.edu/index.html) and regional (e.g. SOCCOM, http://soccom.princeton.edu/; Euro-Argo, http://www.euroargo-edu.org/index.php) networks of profiling floats are an important component of a modern autonomous ocean observing system in the Atlantic. A network of profiling floats helps document seasonal to decadal climate variability and aids our understanding of its predictability. Conventional floats augmented with biogeochemical sensors provide three dimensional information about bio-optical and other biogeochemical variables (Table 5.1.1) that complement the high spatial and temporal resolution of surface remote sensing observations of these parameters. The profiling float network thus helps analyse and improve a new generation of high resolution (1/10°) earth system models to both increase our understanding of the Atlantic Ocean's current workings and make better projections of the future trajectory of the Earth's climate and biogeochemistry.

Targets for the Atlantic Ocean are based on:

- the core Argo mission of measuring temperature and salinity in the open ocean with a nominal spacing of 3° and 10-day sampling, which requires 791 active core Argo floats (Atlantic sector, 60°S to 60°N), with 203 yearly deployments (based on a 3.9 year average lifetime).
- the Biogeochemical-Argo (BCG-Argo) mission of measuring feasible biogeochemical variables on one quarter of the core Argo mission floats, or 197 active BCG-Argo floats (also contributing to the core Argo mission so contributing to the count above, Atlantic sector, 60°S to 60°N)
- Deep Argo mission targets are being identified.

Gliders

Underwater gliders have enhanced capabilities, when compared with profiling floats, by providing some level of manoeuvrability and hence position control. The gliders perform sawtooth trajectories from the surface to depths of 1000-1500m, along reprogrammable routes (using two-way communication via satellite), and can be operated for a few months. Their role in the integrated observing system is to fill the gaps left by other observing platforms. The mission of the EGO (Everyone's Gliding Observatories; http://www.egonetwork.org/) underwater glider network, initiated by European scientists, is to develop a new observational capacity for process studies and operational monitoring of the ocean physics and biogeochemistry with gliders, and thereby going beyond the marine sciences frontiers. In particular, gliders could be deployed to sample most of the western and eastern boundary circulations and the regional seas of the Atlantic, which are not well covered by the present ocean observing system; and in the vicinity of fixed point time series stations. Gliders can operate at higher resolution than the ca. 300 km/10 day one of the Argo profiling float network, and the even sparser ship-based observations. Therefore, glider-based observations have a great potential to address regional and coastal issues, which are so important for societal applications.

Targets for the Atlantic Ocean have not been set, but are subject of discussion with GOOS and JCOMM structures.

Moorings

A network of long-term, high-frequency (< 1 month) moored buoy and fixed ship stations that provide time-series measurements of many aspects of the ocean's surface and depths using advanced sensors in the open ocean is mainly coordinated by OceanSITES (http://www.oceansites.org/). OceanSITES typically aim to collect multidisciplinary data worldwide from the full-depth water column as well as the overlying atmosphere. While there are relatively few moorings with carbon and biogeochemical sensors in the Atlantic, the expanding network will be essential in detecting long-term trends in the carbonate system, oxygen, bio-optical properties, and macronutrient availability, thereby capturing changes in the key Atlantic biogeochemical phenomena: spring bloom primary and export production, anthropogenic carbon flux to the mixed layer and its storage in interior ocean, upwelling, deoxygenation and ocean acidification.

The Prediction and Research Moored Array in the Atlantic (PIRATA) is a program designed to study ocean-atmosphere interactions in the tropical Atlantic that affect regional climate variability on seasonal, interannual and longer time scales.

Targets for the Atlantic Ocean are maintenance of the 18 moored buoys in the PIRATA array, at present supported by France, the USA, and Brazil.

Drifting buoys

The Data Buoy Cooperation Panel (DBCP) has been working for decades to design standardised drifting buoys to suit observational requirements for meteorological and oceanographic applications. DBCP and IOCCP are working together to add biogeochemical sensors on drifting buoys, as currently only a limited number of biogeochemical EOVs are being measured on these platforms.

Targets for the Atlantic Ocean are based on the global mission of one float every 5°, reporting four times daily at minimum, ideally more often to resolve the diurnal cycle of temperature, or about 320 active floats. Their average lifetime is about one year, so that number have to be deployed yearly.

Sediment traps

Sediment traps are containers deployed on moored or drifting buoys for a period up to a year with the goal of estimating how much of the organic material produced in the surface is being recycled on its way to the ocean interior. Knowledge of the regional and seasonal differences in the rate of transport of nutrients and carbon to the sea floor is essential to proper constraints of the Atlantic and global carbon budgets. While there is no coordinated sediment trap observing network, their regular deployments near the ocean time series sites (Bermuda Atlantic Time-Series, CARIACO) could, if extended spatially, become a key component of the integrated Atlantic observing system.

Ship-based hydrography

Despite numerous technological advances over the last several decades, ship-based hydrography remains the only method for obtaining high-quality, high spatial and vertical resolution measurements of a suite of physical, chemical, and biological parameters over the full water column. Ship-based hydrography is essential for documenting ocean changes throughout the water column, especially for the deep ocean below 2 km (52% of global ocean volume not sampled by profiling floats). The Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP; http://www.go-ship.org/) helps develop a globally coordinated network of sustained hydrographic sections (i.e. Repeat Hydrography) as part of the global ocean/climate observing system, providing information on physical oceanography, the carbon cycle, marine biogeochemistry and ecosystems. GO-SHIP provides approximately decadal resolution of the changes in inventories of such biogeochemical variables as carbon, oxygen, nutrients and transient tracers, covering the Atlantic ocean from coast to coast and full depth (top to bottom), with measurements of the highest required accuracy to detect these changes. Ship-based hydrography observing network is critical to addressing questions of how the ocean will respond to increase in dissolved inorganic carbon, decrease in pH, and changes in ventilation strength processes. GO-SHIP data also provide reference data to calibrate autonomous platform sensors that cannot be recovered, and cruises provide a platform for the deployment of many autonomous platfoms as well.

Targets for the Atlantic Ocean are to repeat seven full-basin-spanning repeat sections once per decade at minimum.

Ship-of-Opportunity / Volunteer Observing Ship

The Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) Ship-of-Opportunity Programme (SOOP) makes use of volunteer merchant ships which routinely transit strategic shipping routes. These measure marine meteorological variables, temperature profiles with XBTs, and underway temperature and salinity with TSGs. A number of biogeochemical EOV measurements depends on the SOOP network coverage. So-called 'underway' measurements of pCO_2 in surface sea water and in the air are made routinely by the SOOP network with high accuracies achieved. The SOOP pCO_2 data, potentially supplemented with underway measurements of pH, dissolved inorganic carbon or total alkalinity in the near future, will be vital in describing basin-wide changes in the carbonate system, thereby improving seasonal and inter-annual climate predictions, and better constraining annually updated calculations of the global carbon budget.

Satellites

The space-based observing system is an important component of the Atlantic as well as the Global Observing System. An array of geostationary and polar-orbiting satellites operated by the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) sample the Atlantic and global surface ocean on unprecedented spatial and temporal scales. Remote sensing of SST and SSH form the basis of weather and ocean forecasting system input, and remote sensing of sea state, ocean surface vector stress, sea ice, and SSS contribute as well to the estimate of surface air-sea fluxes. Remote sensing observations of chlorophyll-a, coloured dissolved organic matter (CDOM) and particle backscattering are key to describing the dynamics of suspended particulates in the ocean, which in turn are essential to monitoring and better predicting such phenomena as the spring phytoplankton bloom and associated net primary production fluxes, nutrient and organic matter coastal inputs, and potentially also changes in upwelling and ventilation strength.

HF Radar

A rapidly growing network is a new element of GOOS, focused on coastal surface current observations.

Sea level gauges

Coastally-based sea level gauges provide information for confirmation of tsunami early warning and to monitor local sea level change related to time scales from storm surges to climate change.

Biological and ecological observing networks

Numerous observing networks, largely in situ but including space-based systems as well, are taking sustained observations of biological and ecological variables in the Atlantic Ocean. No Atlantic-wide targets are in place.

An ongoing effort by the GOOS Biology and Ecosystems Panel is mapping the measurements taken, and this information will be included in the 2017 AtlantOS Deliverable 1.3 on capacities and gaps for sustained ocean observations in the Atlantic.

6 Conclusions

This Initial AtlantOS Requirements Report is a collection of the present state of requirements for sustained ocean observing based on pre-existing processes focused on climate, operational ocean services, and ocean health at the global, regional, and even national scales. It brings these together into the common *Framework for Ocean Observing* to encourage a common trans-Atlantic approach and to encourage integration and common priority-setting.

The development of the report highlights a number of significant challenges that the AtlantOS project should address as the work of developing requirements, identifying capacities and gaps, and developing a final set of recommendations based upon the innovation actions of the different work packages comes together.

These include:

- The tendency for climate, operational ocean services, and ocean health-related recommendations at global and regional scales to be developed in isolation - they need more explicit integration to work towards a more integrated and efficient observing system. This is particularly true for the emerging area of sustained observations for ocean health and ecosystems-based management.
- A lack of traceability for key observing network targets and recommendations - the optimal mix of observing platforms to measure the required space and time scales for the needed applications and scientific challenges probably require a more methodical and systematic approach to each application and scientific challenge, with the common *Framework* in mind so that recommendations are both traceable to source and reasoning, as well as compatible to avoid duplication of observing systems.
- The need to be more explicit about not just observational requirements, but the requirements on each step of the value chain identified in Figure 2, which will demand stronger partnerships, starting with data management activities.

The AtlantOS project is designed to work in scientific evaluation activities, engagement, and innovation that will update this requirements document by 2019. Intermediate AtlantOS project deliverables on present capacities, gaps, and the adequacy of the Atlantic Ocean observing system, as well as ongoing work under GOOS, will provide other opportunities for the project, through its General Assembly, to review updates on requirements.

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Annex 1 OSPAR common indicators 2014

‘OSPAR-wide’ common indicators

Indicator code	Description
D1/6 BentHab2	Multi-metric indices
D5 nutrient conc	Winter nutrient concentrations
D5 chlorophyl	Chlorophyll concentration
D5 oxygen	Oxygen
D8 metals (biota)	Metal (Hg, Cd, Pb) concentrations in biota
D8 metals (sedim)	Metal (Hg, Cd, Pb) concentrations in sediment
D8 PCBs (biota)	PCB concentrations in biota
D8 PCBs (sedim)	PCB concentrations in sediments
D8 PAHs (sedim)	PAHs concentrations in sediments
D8 PAHs (biota)	PAHs concentrations in biota other than fish
D8 Organotin (sedim)	Organotin concentrations in sediments
D8 PBDE (biota)	PBDE concentrations in biota
D8 PBDE (sedim.)	PBDE concentrations in sediments
D8 imposex	Imposex/intersex
D10 on beach	Beach litter
D10 on seabed	Litter on the seabed
D11 impulsive noise	Impulsive noise

Bay of Biscay and Iberian Coast

D4 FoodWeb 4	Changes in average trophic level of marine predators (cf MTI)

D1 PelHab 1	Changes of plankton functional types (life form) index Ratio
D1 PelHab 3	Changes in biodiversity index (s)
D5 input water	Waterborne nutrient inputs

Region III – Celtic Seas

D1 Birds 1	Species-specific trends in relative abundance of non-breeding and breeding marine bird species
D1 Fish Ceph 1	Population abundance/biomass of a suite of selected species
D1 Fish Ceph 2	OSPAR EcoQO for proportion of large fish (LFI)
D1 Fish Ceph 8	Distributional pattern within range of a suite of selected species
D1 PelHab 1	Changes of plankton functional types (life form) index Ratio
D4 FoodWeb 3	Size composition in fish communities (LFI)

Region II – Greater North Sea

D1 Mammals 3	Abundance of grey and harbour seal at haul-out sites & within breeding colonies
D1 Mammals 4	Abundance at the relevant temporal scale of cetacean species regularly present (incorporating previous D1 M2 "Distributional range and pattern of cetaceans species regularly present")
D1 Mammals 5	Harbour seal and Grey seal pup production
D1 Mammals 6	Numbers of individuals within species being bycaught in relation to population
D1 Birds 1	Species-specific trends in relative abundance of non-breeding and breeding marine bird species
D1/6 Birds3	Breeding success/failure of marine birds
D1 Birds 6	Distributional pattern of breeding and non-breeding marine birds
D1 Fish Ceph 1	Population abundance/biomass of a suite of selected species
D1 Fish Ceph 2	OSPAR EcoQO for proportion of large fish (LFI)
D1 PelHab 2	Plankton biomass and/or abundance
D5 input water	Waterborne nutrient inputs
D5 input air	Atmospheric nutrient inputs
D5 Phaeocystis	Species shift/indicator species: Nuisance species Phaeocystis
D8 input metal	Inputs of Hg, Cd and Pb via water and air
D10 in Fulmar	Fulmar litter ingestion (impact and floating litter)

Annex 2 HELCOM Core indicators 2014

INDICATOR	Tentative measuring parameters
Mammals	
Population growth rate, abundance and distribution of marine mammals (Grey seals, Ringed seals, Harbour seals, Harbour porpoise)	Abundance during moulting time of grey seals and harbour seals and breeding time of ringed seal
Pregnancy rates of the marine mammals	Corpus albicantia (CA) in spring samples, also documenting uterine obstructions and leiomyomas in grey seals and ringed seal
Nutritional status of seals	Sternum blubber thickness [mm] in by-caught and hunted animals (primary), prevalence of endoparasites and intestinal ulcers (secondary)
Birds	
White-tailed eagle productivity	Nestlings/pair, broodsize and breeding success

Abundance of waterbirds in the wintering season	Abundance based on national census every 3 years of 12 species distribution mainly aerial survey methods.
Abundance of waterbirds in the breeding season	Abundance. Species dependent e.g. common eider and sandwich tern nest counts in census areas, common guillemot census in main breeding colony (SE) with daily observations of egg-laying, hatching, chick mortality and chick absence, great cormorant nest counts in main colonies
Number of drowned mammals and waterbirds in fishing gears	Number of animals (any documented species)
Fish	
Abundance of key fish species	Catch per unit effort (CPUE) using specified gill nets. (Commercial catch per effort based on gear type to be considered)
Abundance of fish key functional groups	Catch per unit effort (CPUE) using specified gill nets. (Commercial catch per effort based on gear type to be considered)
Proportion of large fish in the community	Biomass of selected species in selected size classes
Abundance of sea trout spawners and parr	Parr densities (electrofishing in rivers and streams), assessing availability of suitable habitat
Abundance of salmon spawners and smolt	Densities of parr (electrofishing), automatic fish counters for adult spawners, trapping and tagging of smolts, assessing availability of suitable habitat.
Pelagic habitat	
Zooplankton mean size and total abundance	Zooplankton abundance and biomass
Benthic habitat	
State of the soft-bottom macrofauna communities	Community abundance
Population structure of long-lived macrozoobenthic species	Size distribution of selected species, automated methodology being tested
Red-listed benthic biotopes	Area covered by and quality of biotopes
NIS	
Trends in arrival of new non-indigenous species	Number of detected species every 6 years
Eutrophication	
DIN (winter)	Concentration of chemical/nutrient/pollutant in water column
DIP (winter)	Concentration of chemical/nutrient/pollutant in water column
Chlorophyll-*a* (summer)	Concentration of Chlorophyll a
Secchi depth (summer)	Transparency of water column
Deep bottom oxygen debt	Concentration of oxygen, salinity (profiles)
Hazardous substances	
Polybrominated biphenyl ethers (PBDE): BDE-28, 47, 99,100, 153 and 154	Concentration in fish (cod liver, herring muscle), bivalves (blue mussel) and guillemot eggs. And/or sediment.
Hexabromocyclodocecane (HBCDD)	Concentration in herring muscle, cod liver, blue mussels, guillemot egg, herring gull egg and/or sediment.

Perfluorooctane sulphonate (PFOS)	Concentration in herring liver and muscle, eel liver, flounder liver, perch muscle, blue mussels, guillemot eggs. (seals)
Polychlorinated biphenyls (PCB) and dioxins and furans: CB-28, 52, 101, 118, 138, 153 and 180: WHO-TEQ of dioxins, furans –dl-PCBs	Concentration in herring muscle, perch muscle, flounder liver, cod liver, blue mussels, common guillemot eggs,
Polyaromatic hydrocarbons and their metabolites: US EPA 16 PAHs / selected metabolites	Concentration in blue mussel, soft shell clam, herring muscle, eelpout bile, dab bile, cod bile, surface sediment,,
Metals (lead, cadmium and mercury)	Concentration in whole herring, whole perch, flounder liver and muscle, cod liver and muscle, common dab liver, blue mussels, soft shell clam, Baltic clam
Radioactive substances: Caesium-137 in fish and surface waters	Concentration in flatfish muscle, herring muscle, surface water.
Tributyltin (TBT) and imposex	Concentration of TBT in blue mussels, soft shell clam, fish (liver), surface sediment (secondary), (water optional). Imposex in gastropod snails.

Annex 3 Links between Societal Drivers, Scientific Questions and corresponding identified biogeochemical EOVs

Societal Drivers	**Scientific Questions**	**Biogeochemical Phenomena to Capture**	**EOVs**
The role of ocean biogeochemistry in climate	How is the ocean carbon content changing?	Air-sea flux of CO_2, Anthropogenic carbon flux to ocean's mixed layer, Anthropogenic carbon storage in ocean interior, Net community production, Export production, Organic carbon reservoir, Ventilation strength, Upwelling	Dissolved Oxygen, Inorganic Macronutrients, Carbonate System, Transient Tracers, Suspended Particulates, Stable Carbon Isotopes, Dissolved Organic Carbon
	How does the ocean influence cycles of non-CO_2 greenhouse gases?	Upwelling, Ventilation strength, Deoxygenation	Dissolved Oxygen, Nitrous Oxide
Human impacts on ocean biogeochemistry	How large are the ocean's "dead zones"	Deoxygenation, Ventilation strength, Extent of hypoxia	Dissolved Oxygen, Inorganic Macronutrients, Carbonate System,

	and how fast are they changing?		Transient Tracers, Suspended Particulates, Nitrous Oxide
	What are the rates and impacts of ocean acidification?	Anthropogenic carbon storage in the interior ocean, Ocean acidification	Dissolved Oxygen, Inorganic Macronutrients, Carbonate System, Transient Tracers, Suspended Particulates, Stable Carbon Isotopes, Dissolved Organic Carbon
Ocean ecosystem health	Is the biomass of the ocean changing?	Net community production, Export production	Dissolved Oxygen, Inorganic Macronutrients, Carbonate System, Suspended Particulates
	How does eutrophication and pollution impact ocean productivity and water quality?	Extent of hypoxia, Removal rates of dissolved organic matter fractions, Eutrophication, Pollution	Dissolved Oxygen, Inorganic Macronutrients, Suspended Particulates, Nitrous Oxide, Dissolved Organic Carbon

Annex 4 Table linking observing elements to biogeochemical EOVs

Green – autonomous, blue – ship-based, orange – remote sensing. Spatial and temporal scales captured by the observing elements measuring individual biogeochemical EOVs are described in the respective biogeochemical EOV specification sheets in the Appendix.

Observing element	**EOVs (Sub-Variables measured)**
Profiling Floats	Biogeochemistry: Dissolved Oxygen, Inorganic Macronutrients (NO_3), Carbonate System (pH), Suspended Particulates
Gliders	Biogeochemistry: Dissolved Oxygen, Inorganic Macronutrients (NO_3), Carbonate System (pCO_2, pH), Suspended Particulates
Moorings	Biogeochemistry: Dissolved Oxygen, Inorganic Macronutrients (NO_3), Carbonate System (pCO_2, pH), Suspended Particulates
Drifting Buoys	Biogeochemistry: Inorganic Macronutrients (NO_3), Carbonate System (pCO_2, pH)
Sediment Traps	Biogeochemistry: Suspended Particulates
Ship-based Hydrography (including Repeat Hydrography)	Biogeochemistry: Dissolved Oxygen, Inorganic Macronutrients (NO_3, PO_4, Si), Carbonate System, Transient Tracers, Suspended Particulates, Nitrous Oxide, Stable Carbon Isotopes, Dissolved Organic Carbon
Ship-based Time-Series^	Biogeochemistry: Dissolved Oxygen, Inorganic Macronutrients (NO_3, PO_4, Si), Carbonate System, Nitrous Oxide, Stable Carbon Isotopes, Dissolved Organic Carbon
Ship-of-Opportunity	Biogeochemistry: Dissolved Oxygen, Inorganic Macronutrients (NO_3, PO_4, Si), Carbonate System (pCO_2, DIC*, pH*), Suspended Particulates, Nitrous Oxide*, Stable Carbon Isotopes
Satellites	Biogeochemistry: Suspended Particulates

*Planned future capability of the observing element.

^The Ship-based Time-Series network is described in section 5.1. under Moorings, because it refers to a network of moored buoys maintained by ships, and with ship-based data collection.