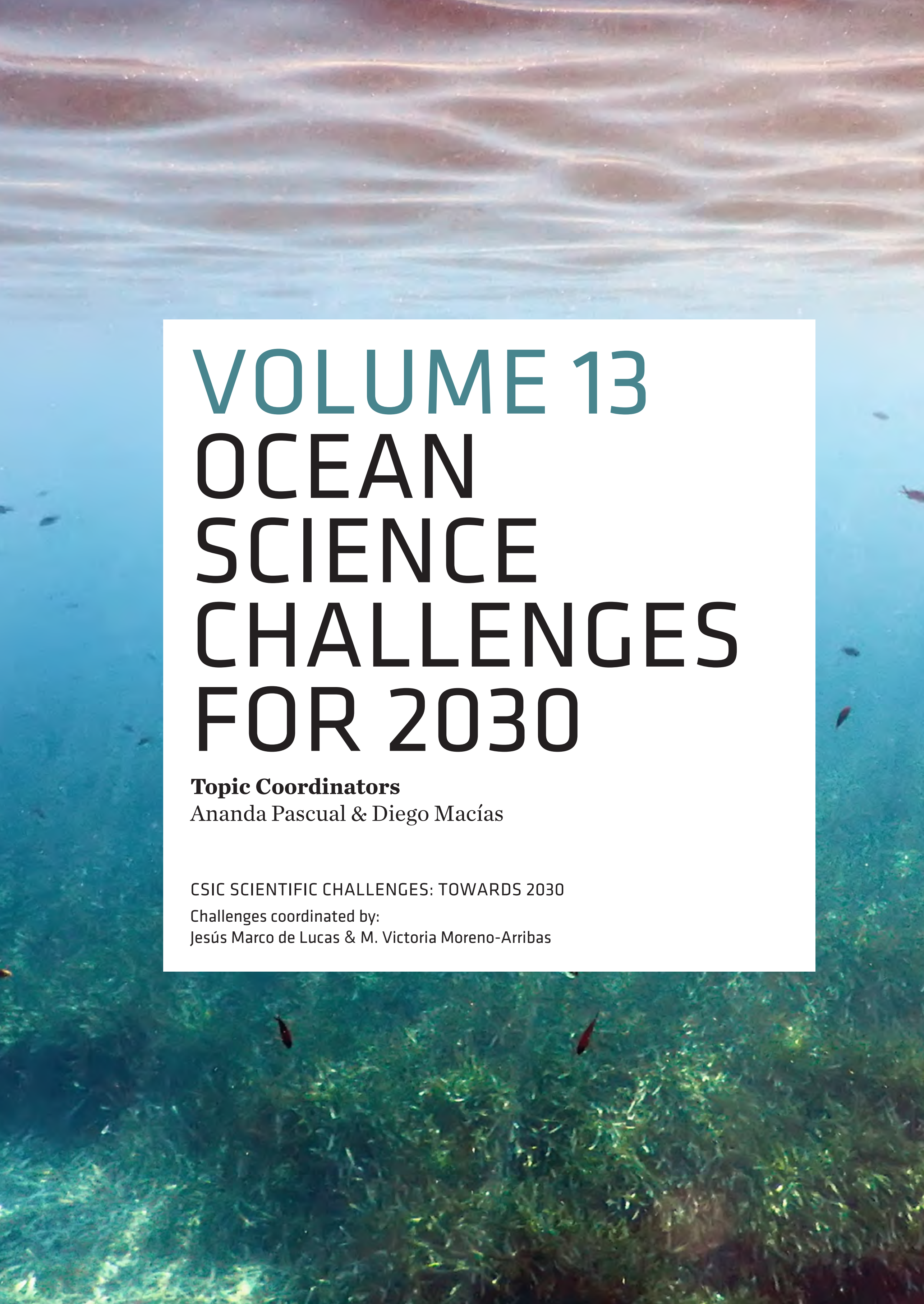

VOLUME 13
OCEAN SCIENCE CHALLENGES FOR 2030

Topic Coordinators
Ananda Pascual & Diego Macías

CSIC SCIENTIFIC CHALLENGES: TOWARDS 2030

Challenges coordinated by:
Jesús Marco de Lucas & M. Victoria Moreno-Arribas

VOLUME 13

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CSIC SCIENTIFIC CHALLENGES: TOWARDS 2030

What are the major scientific challenges of the first half of the 21st century? Can we establish the priorities for the future? How should the scientific community tackle them?

This book presents the reflections of the Spanish National Research Council (CSIC) on 14 strategic themes established on the basis of their scientific impact and social importance.

Fundamental questions are addressed, including the origin of life, the exploration of the universe, artificial intelligence, the development of clean, safe and efficient energy or the understanding of brain function. The document identifies complex challenges in areas such as health and social sciences and the selected strategic themes cover both basic issues and potential applications of knowledge. Nearly 1,100 researchers from more than 100 CSIC centres and other institutions (public research organisations, universities, etc.) have participated in this analysis. All agree on the need for a multidisciplinary approach and the promotion of collaborative research to enable the implementation of ambitious projects focused on specific topics.

These 14 "White Papers", designed to serve as a frame of reference for the development of the institution's scientific strategy, will provide an insight into the research currently being accomplished at the CSIC, and at the same time, build a global vision of what will be the key scientific challenges over the next decade.

VOLUMES THAT MAKE UP THE WORK

1 *New Foundations for a Sustainable Global Society*
2 *Origins, (Co)Evolution, Diversity and Synthesis of Life*
3 *Genome & Epigenetics*
4 *Challenges in Biomedicine and Health*
5 *Brain, Mind & Behaviour*
6 *Sustainable Primary Production*
7 *Global Change Impacts*
8 *Clean, Safe and Efficient Energy*
9 *Understanding the Basic Components of the Universe, its Structure and Evolution*
10 *Digital and Complex Information*
11 *Artificial Intelligence, Robotics and Data Science*
12 *Our Future? Space, Colonization and Exploration*
13 *Ocean Science Challenges for 2030*
14 *Dynamic Earth: Probing the Past, Preparing for the Future*

CSIC scientific challenges: towards 2030
Challenges coordinated by:
Jesús Marco de Lucas & M. Victoria Moreno-Arribas

Volume 13
Ocean Science Challenges for 2030

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VOLUME 13 SUMMARY

ABSTRACT

The ocean is a fundamental element for the Earth and for the wellbeing of human societies. It influences weather and climate, impacting sectors such as marine ecosystems, economy, tourism, and human health. Urgent actions are demanded to help in understanding and managing the ocean in a multidisciplinary and integrated way. Here we present the major ocean research challenges for the next decade, CSIC contributions and leadership.

KEYWORDS

ocean observation

ocean variability and climate

living ocean | ocean health | hazards

polar oceans | coastal areas

big data and artificial intelligence

oceans and society

OCEAN SCIENCE CHALLENGES FOR 2030

Topic Coordinators
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EXECUTIVE SUMMARY

The ocean is an integral component of the Earth's climate system. It covers 71% of the Earth's surface and acts as its primary reservoir of heat and carbon, absorbing over 90% of the surplus heat and about 30% of the carbon dioxide associated with human activities, and producing half of the oxygen we breathe. The ocean is also a complex and multidisciplinary system with structures and underlying processes ranging from turbulence to the climate that we need to understand for sound and knowledge-based management of a system that is essential for life on Earth.

Furthermore, human actions and activities are drastically changing the function of our ocean in multiple and interconnected aspects. With these caveats in mind, marine researchers at the Spanish National Research Council (Spanish: Consejo Superior de Investigaciones Científicas, CSIC) have identified nine outstanding scientific challenges that we must face in the next decade(s) in order to support a healthier, safer, more resilient and sustainable future for our oceans and societies, in line with the priorities set by supranational institutions such as the United Nations (UN), the Intergovernmental Panel on Climate Change (IPCC) or the European Commission (EC).

The first challenge tackles the needs for **sustained and integrated ocean observations** as a requisite for understanding the ocean's state and variability and its role in climate regulation. Indeed, the second challenge addresses **ocean variability and climate**, exploring both physical and biogeochemical processes that

influence and determine Earth's climate. In the third challenge, **achieving a resilient living ocean**, the focus is shifted to understanding how to preserve ocean's life and biodiversity while still maintaining the flow of ecosystem services. The fourth proposed challenge focuses on **ocean health**, understood in a wide concept including how human actions are impacting the state and health of marine ecosystems and how these impacts are influencing human health through diverse feedback mechanisms. **A safer ocean** is the goal of the fifth challenge, in which the need of a better understanding about natural and anthropogenic hazards (defined as infrequent but intense and/or severe events) and ways to mitigate their impact are explored for the multidimensional marine systems. Then, the attention shifts to one of the most fragile and critical marine environments in the sixth challenge, the **polar oceans**. These regions are suffering the largest impacts from climate change while their functioning and role in climate regulation are still largely unknown. On the seventh challenge, key and emblematic coastal ecosystems of Spanish shores are identified, being their main problems discussed in terms of future needs and priorities. Attaining a **sustainable coast**, where more than half of the world's population lives, in a changing ocean is the main aim of this chapter. The eighth challenge steps into the emerging field of **big data and artificial intelligence applied to ocean sciences**. Thus, the main constraints and applications of big data to ocean research are explored and potential solutions are deeply exposed in this chapter. The final challenge (nineth), **oceans and society**, explores the multiple connections existing between these strongly dependent systems. Moreover, aspects such as responsible research and innovation, governance, management, ocean literacy, and education are explored and detailed in this last chapter.

INTRODUCTION

The ocean is a prime component of the Earth's system, providing humans with valuable ecosystem services such as climate regulation, food, energy, mineral resources, and cultural and recreational services. Oceans and seas are key lungs and farms of our planet; they produce half of the oxygen we breathe and up to the 16% of the animal protein for human consumption. The ocean, covering 71% of the Earth's surface, acts as its primary reservoir of heat and carbon, absorbing over 90% of the surplus heat and about 30% of the carbon dioxide associated with human activities (NASEM, 2017). Consequently, aiming to achieve climate and societal goals for sustainable future oceans are critical(Hoegh-Guldberg et al., 2019; Lubchenco & Gaines, 2019).

Yet, human activities have drastically changed the structure and function of the sub-systems of our planet (atmosphere, biosphere, etc.) and their major components (e.g. greenhouse gases). Oceans also trigger some major natural hazards, which threaten lives, critical infrastructures, and the economy (e.g. sea-level rise). The health and productivity of our oceans are severely endangered by climate change, overexploitation, ocean acidification, deoxygenation, excess nutrients, chemical pollutants, and plastics. Human activities are, thus, degrading the ocean in many ways: from altering their ecosystems to impacting their provided system services (e.g., Halpern et al., 2015). The size and magnitude of this set of environmental changes has forced scientists to suggest that we are living in a new geological era, called '*Anthropocene*' (Steffen et al., 2011), in which human activities is the biggest forcing. The growing human impacts on the ocean and their potential consequences for global change and their effects on wellbeing have been clearly stated on the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019).

In this context, the United Nations (UN) has proclaimed a Decade of Ocean Science for Sustainable Development (2021–2030) to tackle the scientific challenges that are necessary for a sustainable use of natural resources. Within this Decade, the UN wants to encourage the scientific community, the policymakers, the private sector, and the civil society to think beyond 'business as usual' and aspire for a real change (Claudet et al., 2020). The objectives, key areas for action, and problems to be tackled in this decade are attached to the UN Sustainable Development Goals (SDGs), particularly constrained within Goal 14: Life Below Water.

A similar view has been recently adopted by the European Commission (EC) with its' research and innovation mission on 'healthy oceans, seas, coastal and inland waters' within the 'Horizon Europe' programme (COM/2018/435). In this mission, the EC recognizes human impacts on marine ecosystems and their importance for human wellbeing. This mission, thus, aims to raise awareness of the ocean's key roles among citizens and help to develop solutions on a range of issues using multidisciplinary and transdisciplinary approaches beyond the classic 'silos' attitude to science. As stated by the EC for its 'mission oceans': "*a major challenge is to tackle marine and freshwater ecosystem degradation and to create a sustainable, circular, and blue economy that is based on sufficient quantities of water as well as on healthy and functioning freshwater and marine ecosystems for the benefit of the current and future generations.*"

This mission on ocean health is also inbred on the new approach of the EC to make Europe the world leader on green growth, pushing for a climate-neutral, sustainable, and productive Blue Economy. The European *Green Deal*, announced in the political guidelines of the Commission 2019-2024, puts at the heart of EU actions the transition towards more sustainable and socially fairways of producing, consuming and trading, while preserving and restoring our ecosystems. Prevention and removal of pollution (chemical, physical, bacteriological, nutrients, etc.) pave the way towards the EU ambition of zero pollution, which will be necessarily driven by behavioral and socio-economic changes.

During the last decades, ocean science has made great progresses in exploring, describing, understanding, and enhancing our ability to predict changes in the ocean system. However, there is still a need to fully understand the magnitude of the current problems in order to implement more effective solutions (Visbeck, 2018; Laffoley et al., 2019). Highly inter- and trans-disciplinary topics and approaches are internationally encouraged in the field of marine sciences. The response of marine ecosystems to a changing ocean can be particularly difficult to predict or even observe in remote habitats such as polar regions, the deep sea, and the high seas, as well as in many territorial waters that lack regular biological monitoring (Murphy et al., 2016; Levin and Le Bris, 2015). These changes can scale up regionally, which highlights the need of ambitious research efforts targeting these relatively poorly known and iconic systems.

Managing the ocean and its natural resources requires that biodiversity and climate concerns permeate all sectors—spatial planning, fishing, energy exploration and production, shipping, coastal development, tourism, and others—, as well as all national, regional, and local development and planning policies and programs (Claudet et al., 2020). Hence, effective solutions must support the integration of human and natural systems (Liu et al., 2015; Thiault et al., 2019), and recognize and manage social-ecological tradeoffs (Ingeman et al., 2019).

As humans impact oceanic systems on every spatial scale (from local pollution to climate change), the '*Anthropocene*' should be fully integrated across all subsequent challenges. Acknowledgment of humans as an interactive and dominant force necessitates the full inclusion of the anthroposphere in Earth System analyses, so long gone are the days when Earth science used to encompass only natural scientists. We must, therefore, move beyond traditional disciplinary boundaries, and engage with those working on complementary aspects of marine research. New synergies across disciplines in physical, natural, and social sciences, as well as humanities, engineering, business, and other fields, should promote new knowledge to inform sustainable development options for our oceans and seas (Claudet et al., 2020). Designing and deploying integrated approaches will lead to systemic solutions regarding the ocean's health and planetary boundaries.

In the same line, science-policy integration should be fostered, as evidence-based decision making should be fully rooted in science. We need to produce science that fits the policy-maker needs so that it can be better transferred into action (Dilling and Lemos, 2011). It is, hence, necessary to improve the way in which scientific results can quickly and effectively inform action, and how we measure the impact of global and regional policies on the ocean (Claudet et al., 2020). To achieve and maintain a sustainable development promoted from the political leaders, mission-driven science (sensu Mazzucato, 2018) is needed to inform policies and raise the knowledge bar of all stakeholders.

In this international setting, the Spanish National Research Council (Spanish: Consejo Superior de Investigaciones Científicas, CSIC), as the largest research institution in Spain, aims at defining the future challenges to be tackled within the context of ocean research. The challenges listed in the present work have been identified by CSIC researchers taking into account their expected positive impact for the society and considering recent scientific developments, societal needs, and the priority research lines defined at international levels. By definition, challenges are characterized by its large complexity, their need to be tackled by multi- and trans-disciplinary teams, and the uncertainty about their full achievement. They represent, thus, the current boundaries of the ocean sciences, which have been defined taking into consideration the key aspects detailed above.

The challenges described in this chapter represent the areas where CSIC will concentrate its efforts in pushing the limits of scientific knowledge to support a healthier, safer, more resilient and sustainable future for our society and our oceans along the next decades. They are deliberately multi- and inter-disciplinary reflecting the need to tackle current marine challenges simultaneously and not sequentially (Lubchenco et al., 2015). This list is not exhaustive nor closed, but it will be regularly updated in order to account for the future development and needs of our society. Furthermore, this work also presents

CSIC leadership and capacities to achieve the challenges, as well as the resources needed to fulfill those aims. CSIC challenges are fully aligned with SDGs and the recent UN initiative declaring the oceans as the new frontier and the Decade of Ocean Science for Sustainable Development (2021-2030). These challenges aim to engage the scientific community, policy-makers, business, and civil society within a framework of joint research and technological innovation. In this regard, CSIC, through its high-level multidisciplinary scientific teams and technological experts, is already contributing to the six societal outcomes of the Decade: a predicted ocean, a safe ocean, a transparent and accessible ocean, a clean ocean, a healthy and resilient ocean, and a sustainably harvested and productive ocean.

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CHALLENGE 1

ABSTRACT

Sustained and integrated ocean observations are vital to establish the ocean state and variability, to understand the ocean's role in climate change. We revise the international frame of ocean observation and the main scientific and societal questions that require multidisciplinary data at a wide range of spatial and temporal scales, and from the nearshore to the open ocean. We present the observing challenges for 2030, CSIC leadership and capacities to achieve them.

KEYWORDS

ocean observation | ocean modelling | ocean variability | sustained research infrastructures | new technologies | research vessels | autonomous systems | remote sensing | multi-platform & integrated systems | climate change | FAIR data | ocean integration

CHALLENGE 1

SUSTAINED & INTEGRATED OCEAN OBSERVATION

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1. INTRODUCTION AND GENERAL DESCRIPTION

Sustained ocean observations[1] are vital to establish the ocean state and variability, to understand the ocean's role in climate change facilitating climate prediction and scenario development and contributing to testing and improving climate models. Ocean observations and modeling are also essential to preserve ocean's health and to respond to real time society needs at regional and local scales, to assure the sustainability of natural resources, the preservation and science-based management of the marine and coastal environment, and to respond and manage marine geo-hazards. The international frame for science, technology and society driven questions that require ocean observation and that need to be addressed in a 2030 horizon is well established (NASEM, 2017) and specific details are provided in the other challenges from the CSIC Ocean Strategic Theme.

Research infrastructures and international cooperation are two key elements of ocean observation at CSIC[2]. Research vessels continue to be essential, especially because they allow multidisciplinary teams of scientists, technical

1 To be understood in all this challenge as considering both in situ & remote observations, modeling and data, therefore covering the whole ocean data value chain.
2 Plan Estratégico del CSIC en Grandes Infraestructuras de Investigación (y propuesta de Plan de Acción 2020-2021), Torné et al., 2020 - http://dx.doi.org/10.20350/digitalCSIC/12502.

staff and students working together on a common goal and they also provide a platform for enabling other infrastructures, such as autonomous and remotely operated vehicles; samplers and sensors; moorings, ocean bottom and cabled systems, etc. In parallel, new monitoring technologies are being progressively implemented in the world ocean leading to major changes in our understanding of its variability. For example, the last decade (2000-2010) has seen the development of the Argo profilers' sustained program that, together with essential satellite and modeling components, contributed to the characterisation and understanding of the large-scale variability in the open ocean. More recently (2010-2020), multi-platform ocean observing systems such as IMOS in Australia, IOOS in the US, or SOCIB in Europe have been implemented, responding to a twofold paradigm change in ocean observation: from single platform to multi-platform ocean observation and from proprietary data to free, open and quality-controlled data, in some cases available in quasi real time. The real challenge for the next decade is the integration of theses new technologies and multiplatform systems to (1) monitor the variability at small scales, e.g. mesoscale/weeks[3] in order to (2) resolve the sub-basin/seasonal and inter-annual variability and by this (3) establish the decadal variability, understand the associated biases and correct them.

Ocean observation is today intrinsically linked to open and quality-controlled data in accordance with TRUST (Transparent, Responsible, User focus, Sustainability, Technology) and FAIR data (Findable, Accessible, Interoperable and Reusable data) principles. Accordingly, the International Oceanographic Data and Information Exchange strongly encourages, within the Quality Management Framework, to develop, implement and manage quality management systems to ensure that data providers can prove their capabilities to provide data and services in compliance with established standards and responsibilities. The quality management systems have to be reviewed to ensure compliance with international ICSU World Data System and IODE standards.

The importance of accurate and reliable observations of the ocean has always been recognized by the scientific community and has been recently remarked by international expert committees such as the Intergovernmental Panel on Climate Change, [IPCC, 2019], and the Committee on Earth Observation Satellites. Assuring their availability is among the objectives of a number of

3 Where the maximum of Kinetic Energy is found, and now, yes, we can monitor at these very high resolution.

international projects, e.g., the European Commission, EC's Copernicus program, the European Space Agency, ESA's Climate Change Initiatives.

The CSIC Ocean Observing challenge is well inserted in this international ocean observing strategy, combining and integrating in situ and remote observations with modeling and data management. In this general frame, significant steps forward have been achieved in recent years in bringing together the wide range of ocean observing networks, forecasting initiatives and data portals, from the open ocean to the coasts. The Global Ocean Observing System (GOOS) is a good example and has resulted in the implementation of the Essential Ocean Variables[4] concept. The new 2030 GOOS Strategy (GOOS, 2019) is an example of a scientific excellence driven observing system that is also considering more and more societal and coastal applications. This **science and society** international strategy is fully in line with the CSIC mission and is again a key element of the CSIC Ocean Observing Challenge.

Therefore, Spanish and European ocean research require a suite of integrated observatories covering a broad range of spatial and temporal scales from the nearshore to the open ocean. Consequently, a CSIC Sustained and Integrated Ocean Observation Plan, well coordinated with the Spanish National R&D&I Plan is essential to be able to respond to science priorities and societal needs. This plan is presented here in a 2030 horizon and will have to be monitored annually and reviewed every 5–10 years.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Addressing the most significant oceanographic research and societal requests in 2030 will require a comprehensive range of ocean observing multidisciplinary platforms and a strategic effort for integration of all the data. In this section we have focused on the science and society questions that are likely, not only to still be relevant, but even more pressing in 2030.

Many of the questions described below reflect challenging scientific problems that will likely take decades to solve, especially if only limited resources are available. These include the need for a global observational framework with sustained ability to monitor changes in the ocean and enhance prediction of the coupled ocean-atmosphere system, a capability to focus on process

4 Three associated GOOS Expert Panels: Physics and Climate, Biogeochemistry, Biology and Ecosystem.

studies that improve understanding, a focus on environmentally sensitive regions and the flexibility to deploy infrastructure during events or emergencies. More specifically:

2.1. Major Science questions

- How will ocean circulation and distribution of heat and carbon affect the climate system, climate impact and climate variability? How do they respond to natural and anthropogenic drivers?
- What processes dominate mixing in the ocean and on what space and time scales?
- What will be the interaction between major ocean currents and the shelf environments and their influence on the ecosystem variability ?
- How will coastal ecosystems and communities respond to multiple stressors?
- How does littoral water quality respond to land based water regimes and uses?
- How will climate change affect the long term variability (volume, heat, salt and nutrient transport) of major boundary currents and cycles of primary production?
- How will ocean acidification affect marine organisms and ecosystems?
- How will regional effects of climate variability affect sustainable fisheries and ecosystem changes?
- How will sea level change on a range of spatial and temporal scales and what are the potential impacts in the nearshore?
- How will ocean observations be more effectively integrated per se and more effectively contribute to ocean forecasting through data assimilation?
- How marine geo-hazards (earthquakes, submarine landslides and tsunamis) can be mitigated?

2.2. Major societal questions

The ocean affects us all. It influences weather and climate, impacting many sectors such as agriculture, marine and coastal activities, marine ecosystems, tourism, living conditions, human health and disaster preparedness, both regional and globally[5]. Sustained ocean observations are needed and vital to

5 JCOMM Observing System Report Card 2018

support the Blue Economy which is predicted to more than double its contribution to the global value-added economy, reaching over $3 trillion by 2030 (OECD, 2016). In this challenge, the Blue Economy is understood as a knowledge-based economy looking to the sea, not really for extraction of natural goods but for data to address societal challenges and inspire solutions. Accordingly, the following societal questions are identified:

- How can we ensure sustainable food production in the ocean?
- What advances will be made in forecasting and mitigation of the impacts of extreme events?
- What advances will give real time response to major natural and anthropogenic hazards (tsunamis, oil spills at sea, etc)?
- How will broadly accessible virtual & distributed data centers and locally held databases, aligned with the FAIR data principles, be established and better ad hoc tools developed to improve access to information by society?
- What are the impacts associated with the changes in sea ice, especially on the general circulation of the ocean, the climate and the primary productivity? Can the most harmful changes be mitigated?
- What is the role of plastics, coastal pollutants and pathogens on human and ecosystem health?
- How will continued innovation contribute to ocean infrastructures' development – including data – and optimization of use?
- What is the optimal way of ensuring the next generation of ocean observing infrastructures and the continuity of the current long-term observations?
- How public leadership in RDI is leading and contributing to innovation – in particular for example in research ships building – and enhancing private sector leadership in Spain[6]?

3. KEY CHALLENGING POINTS

3.1. CSIC Ocean Data Centre and Research Fleet

Decades of marine research activities led by CSIC have produced valuable historical data that are scattered across the institutes and even archived analogically in data reports. Yet a non-negligible amount of data is produced regularly through individual research cruises on board the Spanish fleet. Different

6 The Sarmiento de Gamboa public investment of 25 million Euros initiated in 2002 implied in 10 years, commercial contracts of the order of 300 million Euros for new research vessels at Freire shipyard (SOCIB IP, 2010).

European initiatives such as SeaDatanet, EMODnet, CMEMInstac, among others, have tried to coordinate the compilation of multidisciplinary data – including metadata – acquired from a variety of ocean platforms: ships and all the associated equipments, moorings, coastal sea level stations, drifters, gliders, AUV's, etc. Such data represent an incommensurable wealth of information about the evolution of the oceans in the recent past. It is today well established that we need long and reliable time series to respond to many of today's societal questions and accordingly, and aligned with major EU and international initiatives, we propose to organize all existing historical and present ocean data in a new CSIC Ocean Data Center.

Most of the historical data were collected from research vessels such as the B/O García del Cid, the BIO Sarmiento de Gamboa fom CSIC and the BIO Hespérides, operated by the Spanish Navy but with scientific operations being carried out by CSIC/UTM well trained technicians.

However, both ships are more than 40 and 30 years old respectively and immediate replacement is needed for the B/O García del Cid to assure ship availability for scientists and regional at sea operations with technical and deep-sea capabilities. Finally, it is also important to support the Ministry of Science actions for a new research and logistics polar vessel.

In summary two specific goals and two complementary actions emerge. The goals are:

CSIC Ocean Data Center: the general goal is to foster the recovery, exploitation and preservation of historical data for climate studies and enhance the existing real time and delayed mode data management procedures (mostly but not only at UTM & SOCIB) including data distribution to major European and International data portals (e.g., EMODnet, SeaDataNet, Copernicus, GEOS, PANGEA). The CSIC Ocean Data Center will fill a historical gap and present need and will also contribute significantly to increase CSIC international visibility. For this, we plan to use existing know how and the distributed resources to launch an initiative at CSIC scale to recover historical data, performing all the required tasks (harmonization, quality control, metadata) and to apply similar data management procedures to all new CSIC Ocean & Coastal Data, to guarantee sound archive of all CSIC marine data according to FAIR principles and compliant with the OGC standards on data formats and services. This initiative will also contribute to the reinforcement of Digital CSIC as a recognized standard data repository.

FIGURE 1.1– Research vessels of the Spanish fleet: García del Cid from CSIC (left), Hespérides (center) and Sarmiento de Gamboa (right).

CSIC Regional Research Vessel: to develop a new regional research vessel (30-40 m LOA), to mitigate the ageing of current oceanographic vessels, the limited availability of ship time of the rest of the regional oceanographic fleet and their limited operational capabilities. It should be a multi-purpose platform flexible enough to operate regionally but with deep-sea capabilities and general support for launching and operating a new generation of autonomous and remote vehicles (AUV, ROV, etc.).

The two complementary actions from CSIC are related to ongoing research vessels initiatives from the Spanish Ministry of Science and Innovation and the Spanish Polar Committee. The first one is related to the existing scientific and technical discussion for a New Open Ocean Research Vessel with polar capacities to substitute BIO Hespérides, and the second is related to a New Polar Research & Logistics Vessel to provide direct support to the Antarctic spanish yearly projects developed on polar stations and camps. Further details can be found in the Polar Challenge. CSIC researchers fully support these two initiatives.

3.2. Multi-platform integrated observation and modeling in key selected areas

Understanding ocean variability requires appropriate sampling schemes and different observing platforms and modeling capabilities that are today available, and that were not available ten years ago. Since this cannot be done in all oceanic areas, it is important to focus efforts on science and society driven regions where major advances can be expected.

CSIC is a well-respected international actor in these changes in ocean observation and modeling, well-coordinated in Spain with the initiatives from the Spanish Ministry of Science and Innovation through COCSABO[7], the National Ports Authority and the Spanish Institute of Oceanography. The coordinated access to ocean infraestructures, including on-land sensors (Simarro, 2017), fixed stations (e.g. the Gibraltar Fixed Time series observatory (Flecha, 2015), research vessels, gliders, Argo profilers, drifters and buoys (García-Ladona, 2016; Tintoré et al., 2013), remote sensing, and data access facilities, among others, has positioned CSIC and the Spanish scientific community in a leading position in the observation of the ocean in Europe.

To understand the ocean state and variability from large to local scale and its biogeochemical impacts such as for example, ocean acidification, four specific regions and areas of interest have been identified: the Atlantic Ocean, the Southern Ocean, the Polar Regions and the Boundary Currents, in all of them, fully aligned with major international initiatives and existing and ongoing scientific work and/or alliances. The specific proposal in this challenge is to focus on these regions and make use of existing research vessels transits complemented by existing and new sustained glider transects to obtain the full benefits of the ship based multidisciplinary efforts.

Atlantic Ocean: yearly regular transits to Antarctica performed by both the R/V Hespérides and the R/V Sarmiento de Gamboa are excellent opportunities to advance our understanding on ocean variability at yearly to decadal time scale. Associated with these transits, we also propose to complement these observations with new sustained monthly glider endurance lines from Vigo and Cadiz up to the open ocean (6 gliders in each one) that will provide a weekly to monthly variability of quasi continuous and real time physical and biogeochemical data (further details in the forthcoming Boundary Currents subsection). This initiative will be also linked to the North Atlantic section A-25 of Go-Ship international program. The integrated CSIC data obtained and the associated understanding of ocean variability will be a major asset to enhance CSIC participation in EU initiatives such as EuroSea and forthcoming Atlantic based projects (AIR Center, Horizon Europe, etc.).

Southern Ocean: The Drake Passage is one of the most navigated accesses to Antarctica but less systematically monitored due to its weather. We propose to establish a CSIC fleet of underwater gliders (6 gliders initially) to fill the

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observational gap from the BAE Juan Carlos I to Cabo de Hornos, to provide real time data and monitoring the upper ocean physical and biogeochemical variability. Contacts already exist for local support from INACH and from the US (NOAA – Antarctic Ecosystem Research Division – and Rutgers University).

Polar regions: Maintaining and increasing the technological and logistics capabilities of the current Spanish polar fleet is essential to guarantee the development of polar ocean observations and the implementation of the Spanish Antarctic program. Both the Spanish Polar Committee and the recent strategic plan of CSIC's Research Great Infrastructures point out the necessity of replacing in the near future (2027) the only Spanish ship with polar capabilities, the BIO Hesperides, to be decommissioned. The goal is therefore to design an "oceanographic & logistics" vessel maximizing its efficiency (operating time) with respect to its maintenance and operation costs. In addition, current and forthcoming satellite missions (e.g,. CryoSat, Saral AltiKa, SMOS, CIMR), combined with in situ data from Argo floats, marine mammals, etc., should contribute to improve the quality and coverage of the observations.

Boundary currents: Ocean boundary currents are the hot spot of the societal use of the ocean, for instance for fisheries, transportation, and recreation. Boundary currents play a key role in the transport and distribution of heat and biogeochemical variables. At large scale, they form western and eastern boundary currents, important drivers of climate variability (Rudnick, 2016). In marginal seas, boundary currents flow along the continental slope and drive the main exchange with the open ocean, impacting the marine ecosystems (Ruiz et al., 2019). A cost-effective way to improve the sampling of the boundary currents is through sustained observational programs using autonomous underwater gliders. Gliders are well-suited to sample the Atlantic and Mediterranean Spanish boundary currents (Barceló-Llull et al., 2019) and upwelling systems. Establishing a CSIC glider fleet for sampling key sections of the Atlantic and Mediterranean Spanish ocean boundary currents will contribute to i) complement existing observing systems in Spain, ii) increase the spatial and temporal resolution of measurements, and iii) observe the variability of the boundary currents in real time, across all seasons and under favorable or adverse weather conditions. The plan is to establish a fleet of 30 gliders, 6 in Vigo, 6 in Cadiz, 6 in Barcelona/UTM, 6 in BAE Juan Carlos I/UTM, and 6 in Mallorca at SOCIB&IMEDEA.

3.3. Filling observational gaps: Meso and submesoscale

As introduced in section 1, understanding the three dimensional pathways associated with meso and submesoscale structures and its impact on the large scale ocean circulation and climate is today one of the most important international challenges (Mahadevan et al., 2020). Velocities at mesoscale are also of particular relevance due to their role in a wide range of scientific and societal problems (maritime security, fisheries, coastal interactions, climate prediction, etc.). Sound combination of satellite altimetry with multi-platform in situ observations and modeling is certainly the way forward and CSIC researchers have been significantly contributing to this field with strong international cooperations.

Observations of sea level provided by altimeters since the beginning of the 90s have revolutionized our view and understanding of surface ocean circulation leading to, for example, the quantification of eddy kinetic energy, or the eddy identification and tracking. Nevertheless, the effective resolution of altimetric-based sea level maps is rather low (~ 70 km), which leaves a significant part of ocean mesoscales unobserved, particularly in hot spots of Climate Change such as the Mediterranen Sea. A new mission concept called Surface Water and Ocean Topography (SWOT) will be launched in 2021. SWOT is expected to have an effective resolution between 15-30 km, thus providing measurements of the full mesoscale range. The Western Mediterranean provides an ideal 'pocket sized' study region for understanding upper ocean dynamics, and CSIC's involvement in SWOT will provide readiness and a national capability for observing the major global ocean climates. CSIC is also strongly involved in ESA SMOS mission, the first ever satellite to measure sea surface salinity (SSS) with a technology that has been shown to be able to resolve the mesoscale in the global ocean, and more in particular in the Mediterranean. CSIC leads the production and distribution of SSS maps through the Barcelona Expert Centre[8]. Finally, it is also important to note the importance of the new Sentinel satellites EU constellation that is opening new opportunities for research thanks to new sensors, resolutions, etc., an area where CSIC researchers have been particularly active in the last years.

Another relevant technology to address the growing demand for accurate high-resolution ocean wind forcing from the ocean modeling community is scatterometry. A scatterometer-based correction to global NWP model

8 BEC: Barcelona Expert Centre, Barcelona. http://bec.icm.csic.es/

output has been recently developed, which successfully introduces true smaller scales, corresponding to the physical processes absent or misrepresented by the NWP model (e.g., ocean current and large-scale circulation effects). One goal of the remote sensing community is to add Doppler capability to future scatterometers to allow for simultaneous measurements of surface winds and currents.

Below the mesoscale, the relevance of submesoscales has only been discovered during the last decade. The advent of sustained glider transects (Rudnick, 2016) and high resolution numerical models (McWilliams 2016) has uncovered their relevance not only in ocean dynamics but also for the Earth climate. Submesoscales are characterized by horizontal scales between 100 m and 10 km, vertical scales from 10 to 1000 m and temporal scales from hours to days, what make them difficult to observe. Therefore, a combination of all the available platforms (satellites, oceanographic vessels, gliders, Lagrangian drifters and moored instruments) is required to resolve the complex submesoscale dynamics and their interactions at the mesoscale (Pascual et al., 2017). Some of the platforms necessary for sampling submesoscales (in situ instruments, satellite observations, advanced signal processing tools and theoretical frameworks) exist at CSIC. New resources are needed to expand and foster CSIC capabilities and leadership in international initiatives (e.g. CALYPSO).

Some new tools for high added-value analysis of oceanic observations in the intermediate range of scales have been borrowed from Complex Systems theory. These methods allow, for instance, the identification of lines and surfaces present in the flow that act as barriers to transport, e.g. fronts or eddy boundaries, creating a template of the main routes of fluid transport. These techniques have been originally applied to the sea surface, while including vertical movements is still challenging; but obtaining the three-dimensional transport template is of primary importance to specific marine processes of high societal impact (movement of larvae, sedimentation of microplastics). CSIC researchers have pioneered successful approaches to this, giving rise in some cases to added value products (e.g., AVISO FSLE).

Another novel approach to ocean data processing introduced at CSIC is the use of multifractal techniques. Singularity analysis applied to different remote sensing scalars has been shown to reveal streamlines (Turiel, 2008), and can be used to merge different variables or to improve the description of key variables related to ocean turbulence. Other non-linear methods can be applied to remote sensing images to derive information about the mixed layer depth or the emergence of submesoscale turbulent dissipation pathways. A clear link with other CSIC challenges related with Artificial Intelligence is also clearly evident in particular in relation to quasi automatic quality control and data management procedures for real time and delayed mode.

3.4. Filling observational gaps: marine geohazards and coastal observation

Oceanographic data, combined with integrated predictive models, are crucial to respond to the new challenges facing coastal seas characterized by small temporal and spatial scales. Preservation of coastal seas, dealt in detail in the Coastal Ocean Challenge, implies monitoring their state and variability continuously up to the next decades in order to maintain uses as well as to deliver accurate and reliable ocean services. This, combined with the fact that science has the responsibility to maintain healthy, resilient and sustainable coasts together with the promotion of new scientific insights, are the drivers for the development of coastal observing networks.

Cost-effective solutions for observing processes over large areas of the coasts have to be established in order to better understand the complex interdisciplinary processes in shallow seas in a changing environment and in heavily used coastal areas in order to mitigate global change effects; to provide systemic solutions for the prevention, reduction, mitigation and removal of marine pollution; to promote the transition to a circular and blue economy and to achieve a sustainable use and management of ocean resources.

Among the first coastal ocean observing systems is SOCIB, the Balearic Islands Coastal Ocean Observing and Forecasting System, that was borned from CSIC and IMEDEA, and that aims to deliver new insight into coastal ocean variability combining scientific excellence, technology development and responding to society needs. It was designed as a multi-platform of integrated systems (including buoys, drifters, satellites, ship, gliders, HF radar, ARGO profilers, beach monitoring facilities, etc.) in order to provide quasi real time quality controlled open data for science and society. Maintaining and enhancing today's capabilities is a clear priority as described in Tintoré et al., 2019) where the scientific contributions for the last 10 years were reviewed and the challenges for 2030 analysed. They are outlined next for completeness: (1) Strengthen the existing monitoring and forecasting ocean infrastructure (CMEMS, EMODnet, SeaDataNet and the sub-regional systems). (2) Develop a new monitoring strategy for the hydrology and sediment mass balance at the basin scales, while retaining local relevance. (3) Develop innovative INSPIRE compliant transformation services (cloud-based, etc.) connected to the EMODnet Portals and CMEMS products, based upon an accurate investigation of the stakeholders needs; (4) Strengthen the partnerships between MONGOOS, GOOS, IODE and the atmospheric observing and forecasting community (World Meteorological Organization-WMO) connecting the Mediterranean system to the global met-ocean information infrastructure.

A specific platform of special relevance is the Casablanca oil Platform, 40 km offshore the Ebro river mouth that allows the characterization of interesting geological, physical, biogeochemical, and ecological processes. For its specific position and the available facilities, the site has already been used in the past as a privileged test-bench for satellite missions. Considering the upcoming launch of a number of satellite missions with the capability of measuring either ocean-color or the atmospheric composition the consolidation of its role as a validation site is considered a great opportunity. Also important is the participation of CSIC in the RAIA Observatory since its beginning, being responsible for Cape Silleiro transect, long term deployments of ADCPs and a sediment trap, quality check of the biogeochemical variables and identification of environmental indicators of the observatory.

According to the United Nations (2015), half of the world's population lives close to the coastline, so that a huge number of people and infrastructures are threatened by marine hazards. Marine geo-hazards, and in particular earthquakes, submarine volcanism and landslides, and their associated tsunamis, are amongst the most destructive ones (see *challenge 5. A safer ocean: improving the management of marine hazards*). The study, understanding and mitigation of **marine geohazards**, including the improvement of early warning systems, require offshore geophysical instrumentation [Sallarès, 2019]. In particular ocean bottom seismometers (OBS), long streamer of hydrophones, fiber optic and observatory cables, and geodetic instruments to track motions and vibrations, deep coring systems for paleoseismicity and landslide studies, and ROV and AUV vehicles for sediment imaging and sampling in-situ.

Given the aforementioned high population and infrastructure density of the coastal strip (and as detailed in the Coastal Challenge), properly monitoring the coastal morpho-dynamic evolution is an issue of major social interest. Coastal erosion is due to direct human action (modification of sediment transport in rivers and along the coast), and is accentuated in a scenario of rising mean sea level. A proper observation of the coastal strip includes not only the sea/land interface but also the emerged and submerged morphologies (in the order of ±10 meters). The scientific goal is to be able to observe changes and impacts in any domain of interest in the coastal strip in a cheap, fast and accurate way. While satellites provide information in any part of the globe, its accuracy is still unsatisfactory for this goal and fails to give morphological information other than the shoreline position (besides other problems such as the measuring frequency and cloudiness). The use of imagery techniques (video cameras) has experienced a huge advance in the last three decades since the development of the ARGUS project in 1992, specifically important also when combined with in situ observations. Current applications of these techniques include the observation of the shoreline position and other morphologies such as submerged bars, but also intertidal and submerged bathymetries (among others). Some of the above features can also be obtained with radar stations. Video monitoring systems consider fixed stations with several cameras providing high-resolution information about coastal morphodynamics for decades, as do the different systems managed by CSIC in Spain. At present, the lowering and increasing quality of the drones allow the capability of analyzing the coastal strip at almost any place. Still, the improvement or adaptation of the video-monitoring based algorithms (for shoreline detection, bathymetry, velocity field, waves, etc) remains an open question.

3.5. Ocean integration capabilities

On top of the individual components of observing systems, data and model-data integration are undoubtedly key challenges to be addressed in the next decade. Multidisciplinary observations acquired from a variety of platforms providing information of different variables at different scales need to be planned, distributed and analyzed following an integrated approach to get the maximum benefit out of the investment associated with this observational effort. In particular, integration of this diversity of multi-platform measurements into high-resolution numerical models allows to combine them into a single picture.

As a United Nations 2021-2030 Ocean Decade Programme, the proposal for "Predicting the Global Coastal Ocean"[9], co leaded from CSIC and SOCIB, that has already raised the interest of more than 180 international scientists,

9 https://www.coastspredict.org/

identifies 1) the integrated knowledge of the global coastal ocean and 2) the integration of the coastal and open ocean observing and modeling systems, as two main outputs enabling an increased knowledge and advanced predictions of the global coastal ocean, which are today necessary to provide solutions for the management and sustainable exploitation of the resources.

Integration should first help assembling and coordinating the presently fragmented platform-driven observing system, which also suffers from the diversity of actors involved, from research institutes and governmental agencies to international organizations and private companies. The integration of ocean measurements from satellites, research vessels, seafloor geophysical instrumentation, fixed moorings, tide gauges, drifting buoys, autonomous floats, underwater gliders, autonomous surface vehicles or high frequency radars would largely overcome the sum of the contributions of these components considered individually and fill important gaps in ocean information. CSIC should participate in the standardization of marine data production, with the definition of best practice protocols, including data uploading to CSIC data repositories (see Challenge 1). Supporting the capacity in coastal modeling and in model-data integration through data assimilation is also essential to address the next decade challenges. This integration allows us to unify the representation of coastal processes and their variability, paving the way for an enhanced scientific understanding (De Mey-Frémaux et al., 2019). Advanced techniques will be needed to enable the assimilation of new data types, as well as the incorporation of observations in high-resolution models and large-dimensional systems including the coupling of oceanic, atmospheric and biogeochemical components.

Model–data integration is also essential to address the challenge of the prediction which is required for many societal applications (emergencies associated with oil spills, pollutants and harmful algal blooms, search-and-rescue, fishery management, navigation, marine hazards...). Data-assimilation forecasting capabilities in the ocean are not as mature as they are in the atmosphere, requiring further investigation and specific approaches according to the spatio-temporal scales that need to be addressed and the types of measurements that are incorporated. This model-data integration into operational centers allows timely and detailed information about the marine environment to both scientists and stakeholders[10].

10 see for instance the Copernicus Marine Service in Europe: https://marine.copernicus.eu/

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CHALLENGE 2

ABSTRACT

Oceans cover 71% of the Earth's surface. Most of the solar radiation is absorbed by the oceans. The way the oceans use and distribute this radiation affects the Earth's weather and climate. Advances in our knowledge of the interplay between air-sea interactions, mechanical turbulent mixing and the biological carbon pump remain key to understanding the past, present and future climate scenarios of Earth.

KEYWORDS

climate variability | turbulence
biological pump | hydrological cycle
greenhouse gases | mixing | nonlinearity
carbon processes | marine biota
paleoclimate

CHALLENGE 2

OCEAN VARIABILITY AND CLIMATE

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1. INTRODUCTION AND GENERAL DESCRIPTION

The ultimate driver of Earth's climate is the Sun. Indeed, the Earth's average surface temperature, about 15°C, results from the Sun's luminosity, the average Earth-Sun distance, the Earth's albedo (fraction of incoming radiation that the Earth reflects back to space) and the existence of a greenhouse atmosphere. Without the presence of atmospheric greenhouse gases (mainly water vapour, carbon dioxide CO_2, methane CH_4, nitrous oxide N_2O and ozone O_3) the average temperature at the Earth's surface would be around -18°C.

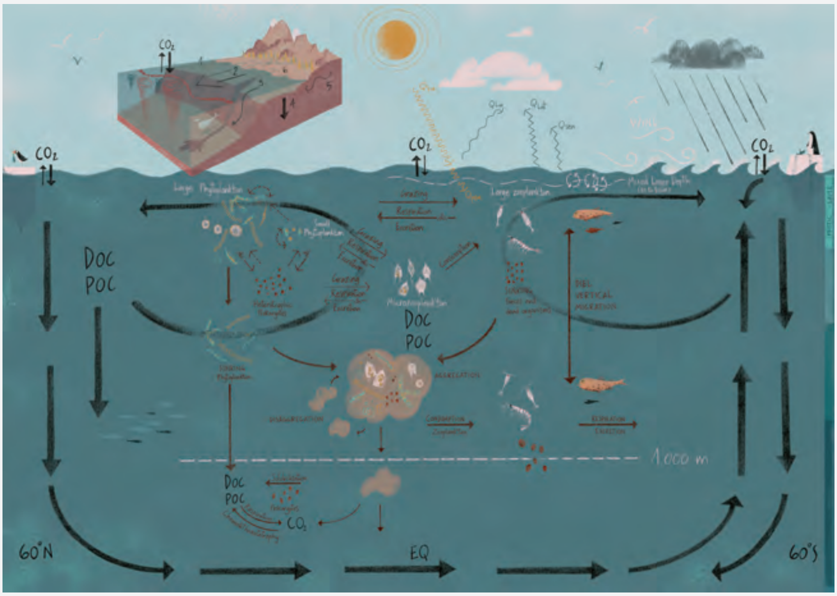
As oceans cover two-thirds of the Earth's surface, most of the incoming solar radiation falls on the ocean surface. The combination of the ocean's low albedo (0.06), large heat capacity (4.2 kJ kg^{-1}) and enormous volume (1.35 billion cubic kilometers) makes the oceans the largest solar energy collector of the Earth's climate system. By storing and distributing heat, and by buffering the atmospheric CO_2 concentration, oceans play a major role in modulating the Earth's climate.

The simplest description of the ocean's structure is that of three layers: a well-mixed and well-lit surface layer or epipelagic zone, a transition layer (thermocline), and the cold deep ocean (Figure 2.1). In the mixed layer, active air-sea exchanges and ocean biological production occur. Photosynthesis in this layer constitutes the basis for marine production and provides vital food resources that help support human population. Below the mixed layer, there is a transition layer in which the temperature rapidly changes from the warmth of the mixed layer to the cold deep ocean of the abyss. Both, the thickness and the temperature gradient of the thermocline depend on season and latitude. The thermocline thickness is quasi-permanent in the tropics and varies according to the season at midlatitudes. At high latitudes, the weak vertical temperature gradients lead to weak thermoclines. The importance of the ocean thermocline in regulating the Earth's climate relies on its capacity to accumulate and distribute heat. In large parts of the ocean, the lower limit of the permanent thermocline (about 1000 m) roughly coincides with the lower limit of the mesopelagic zone (Figure 2.1).

The resulting ocean circulation is turbulent. Oceans develop ephemeral or stable eddies with sizes ranging from the large scale determined by the size of ocean basins (thousands of kilometers) to the scales determined by viscosity (millimeters) (Figure 2.1). These unpredictable eddies of different spatial scales interact, allowing energy to be transferred among the different spatial scales. As this eddy-interaction is non-linear, no analytical or numerical solution is able to account for its full range of scales and only approximations to particular solutions exist. Quantifying the role of ocean eddies for transporting heat, mass, nutrients, and dissolved gases across the oceans continues to be an open challenge. Additionally, the role of small-scale turbulence on the fluxes of dissolved elements to and away from particles and on particle interactions below the centimetre scale also remains a challenge.

The oceans control the atmospheric CO_2 content via two different processes: the solubility and the biological carbon pumps (Figure 2.1). As a result, oceans contain about fifty times more carbon than the atmosphere. Recent estimates suggest that oceans have absorbed more than 152 Pg (i.e. 30%) of anthropogenic carbon from the atmosphere since preindustrial times (Gruber et al., 2019). On the one hand, the solubility pump involves CO_2 air-sea gas exchange, chemical equilibria, downward transport, and mixing of dissolved CO_2 (dissolved inorganic carbon, DIC) in seawater. As the solubility of CO_2 increases in cold water, convective deep water formation at high latitudes carries high

FIGURE 2.1–The three identified Key Challenges about the role of the ocean on the Earth's climate: (1) Role of air-sea interactions (2) Role of the geophysical turbulence and (3) Role of the biological pump · Momentum and buoyancy fluxes on the upper ocean mixed layer are shown. Shortwave solar radiation (Qsw), longwave back-radiation (Qlw), latent heat flux (Qlat), sensible heat flux (Qsen), and solar radiation penetrating the base of the mixed layer (Qpen) · Processes involved in the transport and transformation of carbon in the ocean's biological and solubility carbon pumps are illustrated. In the biological pump, atmospheric CO_2 fixed by autotrophs in the epipelagic domain is involved in different processes, and some of it eventually reaches the deep ocean (> 1000 m) where it is sequestered in timescales >100 yrs. Phytoplankton becomes senescent and sinks as single particles, or as aggregates, while being decomposed by heterotrophic prokaryotes or consumed by animals. Phytoplankton can also be consumed by herbivores, including microzooplankton and larger zooplankton. Sinking zooplankton faecal pellets can also be part of aggregates. Diel vertical migrations of zooplankton and micronekton actively transport dissolved and/or particulate carbon to the mesopelagic, and contribute to the formation of deep scattering layers. Chemolithoautrophic metabolisms can also convert CO_2 to particulate carbon in the deep ocean where inorganic nutrients abound. Dissolved, and also particulate, organic carbon is also transported downward by large scale subduction during water mass formation at high latitudes. The solubility pump is driven by the physico-chemical processes that inject dissolved inorganic carbon from the surface to the ocean interior. Dashed lines correspond to mixotrophy nutrition mode. The role of viruses in the recycling of organic matter is highlighted in the respiration-excretion arrows. Regarding the role of the coastal region to the biological pump, the shown numbers correspond to (1) blue carbon habitats, (2) primary production, (3) canyons, (4) burial, and (5) groundwater.



DIC concentrations to the cold deep ocean. In areas where carbon-rich ocean waters upwell to a warm surface region, a CO_2 outgassing back to the atmosphere occur. Ocean circulation and ventilation of deep waters play a primary driver role in the ocean carbon cycle's response to anthropogenic CO_2. Changes in momentum or buoyancy fluxes in response to warming or alterations in the hydrological cycle might cause a reduction of deep water formation, reducing the ocean uptake of atmospheric CO_2. On the other hand, the biological pump includes all processes through which photosynthetically fixed carbon is transported from surface waters to the deep ocean. These processes contribute to maintaining the vertical gradient of DIC. In spite of the importance of the biological pump, our knowledge about its functioning and mechanisms is very limited, with large uncertainties in the estimate of carbon export from the euphotic zone, in the rates of transformation from inorganic to organic forms, and even more in the amount of organic carbon reaching the deep ocean. Likewise, ongoing anthropogenic changes inducing modifications of ocean dynamics and biogeochemistry (such as increased stratification, nutrient availability, acidification, deoxygenation, addressed in Challenge 4 of this chapter) alter the processes involved in the biological pump and, consequently, trigger significant feedbacks on the Earth's climate.

Advances in observations and in numerical modelling are suggesting novel, yet not well understood, physical, chemical, and biological mechanisms by which oceans modulate the global climate. However, some of these novel mechanisms are still not well reproduced by today's climate models. Complete understanding of these processes, and their interaction, is a required step to improve the accuracy and reliability of climate projections.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

The Paris Agreement (December 2015) was adopted by 189 countries as a global response to the threat of climate change. The Agreement recognizes the need to limit the global planet temperature rise well below 2°C. Recently, the Intergovernmental Panel on Climate Change (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC, 2019) has pointed out the impact of climate change on the ocean and its ecosystems, emphasizing the urgent need of reducing carbon emissions in order to limit warming below 1.5°C, as another special IPCC report stated (IPCC, 2018).

The ocean plays a central role in mitigating climate change by absorbing roughly 30% of the anthropogenically produced CO_2 and over 90% of the human–generated heat. The ocean is experiencing changes more rapidly than expected, and in ways not yet understood. Global Warming is altering ocean circulation, dissolved oxygen levels, nutrient availability in the photic layer, and also changing species distributions, increasing sea level, flooding our coasts, losing coastal habitats, and ultimately impacting on global health (SROCC, 2019). Thus, there is a clear need to advance in understanding of how the ocean and its ecosystems will respond to anthropogenic climate change, including the role of the ocean as a major heat and carbon sink. Advancing in our knowledge of the role of the ocean on the Earth's climate faces complex challenges on subjects such as the air–sea interactions, the geophysical and microscale turbulence and the biological pump. These key challenges require to address the following goals: reducing the hydrological cycle uncertainties, a better understanding of the ocean impact on atmospheric reactivity and clouds, a higher resolution of ocean-atmosphere exchange of greenhouse gases (GHGs), deciphering the subannual variability in the earth system, estimating the contribution of submesoscale processes, resolving the parametrization of mixing in ocean models, improving our knowledge of epipelagic processes, exploring the meso- and bathypelagic domains, understanding the role of the coastal regions, and exploiting the insight from the paleo-perspective.

As indicated by Boucher et al. (2016), research efforts to reduce uncertainties on the magnitude of the response of the climate system to GHGs should not be diminished, as the possible 21st Century GHG emissions pathways depend strongly on it. All these research efforts are critical to reach the ambitious goal of a climate neutral European Union in 2050 established by the European Green Deal (COM/2019/640 final).

3. KEY CHALLENGING POINTS

3.1. Role of air-sea interactions in climate

At the mixing layer, the mechanical and buoyancy fluxes across the air-sea interface enhance air-sea transfer of energy and substances and stir the upper layer of water, overturning and mixing it. Evaporation at the sea surface transfers vast quantities of energy from oceans to the atmosphere (equivalent to 25% of the total heat that the Earth receives from the Sun), linking the Earth's hydrological and energy cycles. Air-sea exchanges at the ocean surface also include the emission of reactive trace gases and aerosols and the fluxes of GHGs that contribute to the atmosphere's heat budget.

Global budgets of freshwater fluxes across the air-sea interface are not calculated directly from observations of evaporation or precipitation, but they are indirectly estimated from remote sensing measurements carried out by multiband passive microwave radiometers and with the help of bulk algorithms or numerical models. As of today, there is a 22% variation in the estimated amount of global rainfall, depending on the atmosphere-ocean model being used to estimate them. Moreover, the hydrologic sensitivity, i.e. the percentage change of mean-global rainfall per unit surface temperature change, also differs between climate models (1-3% K^{-1}).

The surface of the oceans is a ubiquitous source of tiny airborne particles (called aerosols) that have a large ability to regulate the atmospheric chemistry, optics, cloudiness and, ultimately, the Earth's climate. However, the role of marine aerosols in cloud formation and climate remains so uncertain that even the sign of its overall climate forcing (warming or cooling) is unclear (Brooks and Thornton, 2018). One of the reasons for such uncertainty is that not all of the emitted marine aerosols act as cloud condensation nuclei. The composition and size of aerosols determine how effective they are in catalyzing the formation of water droplets or ice crystals.

The world ocean is a substantial contributor to the global budget of atmospheric emissions of long-lived GHGs (such as CO_2, CH_4, N_2O). It has been well established that the global ocean is an important sink for anthropogenic CO_2 as it has absorbed roughly 30% of air emissions since the beginning of the Industrial Revolution, considering uncertainties in sinks calculations and the final imbalance. The ocean contribution to the global carbon budget is an important moderator of climate change, but it is uncertain if it will remain so strong, as the ocean's absorption capacity will decrease in the future. Similarly, the global ocean contribution to the atmospheric CH_4 budget is highly unclear, due to sparse data constraints (Weber et al., 2019). Oceanic CH_4 emissions estimates range from 5 to 25 Tg of CH_4 per year, representing 1–13% of all natural effluxes. Despite the significant contribution of the costal ocean (including deltas, estuaries and intertidal salt marshes) to CH_4 emissions, the dominant source of the marine CH_4 is the seafloor, where the gas is produced biologically in anoxic sediments or released from geological reservoirs at hydrocarbon seeps and degrading CH_4 hydrate deposits. Novel phyto- and zooplankton mediated methanogenesis pathways may produce CH_4 *in situ* in the surface ocean mixed layer, providing a more direct conduit to the atmosphere. As for N_2O, the estimates of its ocean emissions range between 10 to 53% of the combined natural and anthropogenic N_2O sources. N_2O has been measured in the water column of all major ocean basins, in most marginal seas and in many estuaries, with concentrations varying over three orders of magnitude from the open ocean to coastal shelves and semi-enclosed basins. Compared to CO_2, there are few marine N_2O measurements to date, and little is known about seasonal and inter-annual variability, land-ocean gradients, the effects of small scale/mesoscale features and storms. Likewise, the influence of sea ice on N_2O emissions from high-latitude ecosystems is currently unknown.

The three specific goals that need to be addressed to disentangle the role of the air-sea interaction on the Earth's climate are:

- **Reduce the hydrological cycle uncertainties**. The link between the hydrological cycle and the energy cycle means that uncertainties in water budgets translate into uncertainties in the climate energy budget in current climate models. Differences between climate models arise both from differences in physical parameterizations and from the way available information is included in these models. Nevertheless, new streams of data may help reduce these uncertainties. A promising new set of remote sensed observations that may help close the water cycle budget are sea surface salinity (SSS) retrievals from L-band (~1.4 GHz) measurements. As changes in the values of SSS result from the integrated contribution of evaporation, precipitation, advection, diffusion and river runoff, freshwater fluxes may be inferred by combining information about SSS and ocean currents. Systematic retrievals of SSS from satellites started just a decade ago with the launch in 2009 of the Soil Moisture Ocean Salinity (SMOS) mission. However, the error in the retrievals of SSS remains excessively large in some of the regions of high SSS variability (coastal areas and high latitudes). This is due to technological and mission design limitations. Improving SSS retrievals in these regions will help close the hydrological cycle budget. The roadmap to increase the accuracy of SSS maps is to:

  i) Increase our understanding of the nature of the L-band brightness temperature observations.
  ii) Develop multi-mission intercomparison studies.
  iii) Develop *in situ* and remotely-sensed SSS data assimilation advanced schemes into coupled climate models.

iv) Contribute to the design of follow-up L-band Earth-Observing missions.

Advancing through this roadmap requires further improvements about the physics of the micro-wave measurements of the ocean, geophysical transfer functions, ocean modelling and data assimilation.

- **Improve our understanding of the ocean impact on atmospheric reactivity, clouds and climate**. Understanding the link between marine aerosols and clouds requires improving our knowledge about the various processes involved: the biogeochemical processes that produce trace gases and organic compounds in ocean waters; the emission of these compounds through the air-sea interface; the actual formation of the different classes of marine aerosol; and the transition of some of the aerosol components to cloud droplets and crystals. The roadmap to attain an appropriate understanding of the oceanic role on atmospheric reactivity and clouds includes:

v) Assess the complementary roles of volatile precursors of secondary marine aerosol as well as the contributions of labile and refractory dissolved organic matter to the emissions of primary marine aerosol.
vi) Increase our understanding of the distinctive physical, chemical and biological properties of the ocean's surface microlayer (1-1000 μm) mediating the air-sea fluxes.
vii) Improve the observational techniques used to characterize the composition of the organic fraction of marine aerosols.
viii) Obtain quantitative estimates of the marine contribution to cloud condensation nuclei.

Advancing through this roadmap requires further developments in observation techniques and protocols, measurements of new particle formation events in the open ocean, the use of mesocosmos, cloud chambers and transport and chemistry models with appropriate cloud microphysics process models.

- **Reduce uncertainties about the ocean-atmosphere exchange of greenhouse gases (GHGs)**. A main challenge is to constrain the ocean budgets of GHGs and reduce the uncertainties of their contribution to the emissions to the atmosphere through the establishment of harmonized Global Ocean Observation Networks. Meeting this aim will require:

ix) Improve the estimates of marine carbon inputs provided by rivers, and of the estuarine outgassing.
x) Understand the relative importance of the drivers of N_2O production and consumption in the ocean and their response to changing oceanic conditions, such as warming, deoxygenation and acidification.
xi) Increase our knowledge of the role of sea ice caps in GHGs emissions.
xii) Obtain a higher temporal and spatial resolution of air-sea exchange measurement sites and a more precise development of measurement protocols.
xiii) Improve the empirical gas transfer models, including the effects of ocean turbulence.

3.2. Role of geophysical and microscale turbulence on climate

Energy enters the ocean system with rather well defined frequencies – mainly tidal, daily and seasonal, plus intermittent energy supply through the passage of atmospheric perturbations – but evolves towards multiple scales through internal ocean and coupled air-sea nonlinear processes. This evolution is sometimes greatly amplified and gives rise to remarkable events, with high impact in very diverse aspects such as weather, inland climate and fisheries. The way this nonlinear evolution develops is still, in many regards, an enigma.

A fundamental property of ocean turbulent flows, such as oceanic motions, is the non-linear interaction between processes at multiple scales. In the ocean, these scales span ten orders of magnitude, from the submillimeter to the planetary scale. Interactions between such a range of scales cannot be explicitly resolved analytically or numerically, making it necessary to focus on the dynamics of a subrange of scales and to parametrize the effects of the non-resolved ones (Fox-Kemper et al., 2019). However, the details of how processes at different scales interact, the so-called turbulent cascade, are rather complex and still poorly understood, becoming a source of errors in ocean and climate models (Flato et al. 2013).

The outcome of these physical (and biogeochemical) interactions between scales give rise to emerging properties that sustain life itself, from microplanktonic to regional ecosystems and the Earth system. In particular, the transfer of properties that are critical to the Earth's climate – mass, freshwater, heat, nutrients, plankton and many other biogeochemical properties – depends on the residence time at each scale and the interactions among scales. We know, for example, that submesoscale turbulence in one region not only impacts large-scale ocean features locally, but also impacts the ocean dynamics in remote regions. However, we know very little of how this happens.

The three specific goals that need to be addressed to respond about the role of geophysical turbulence on the Earth's climate are:

- **Understand the subannual modes of variability in the ocean**. The reanalysis of historical data has shown the existence of multiple modes of oscillation in the ocean-atmosphere system. A key aspect of these modes is its intermittency, which arises from the nonlinear dynamics of the ocean and the atmosphere and from the different processes driving their interaction, from fast weather perturbations to the intermediate-speed ocean waves and to the slower large-scale gyres and the meridional overturning circulation. The Atlantic modes of variability are a nearby example of the complexity of the problem, from interannual (e.g. North Atlantic Oscillation and the Atlantic El Niño) to multi-decadal and beyond, all the way to the glacial-interglacial 100 kyr cycle. All these intermittent oscillations may have regional (e.g. high precipitation in Sahel during the Atlantic Niño) and global (e.g. a 4-5°C change in the Earth average temperature between the glacial maximum and the interglacial period) climate impacts.

  The roadmap to understand the impact of the various ocean variability modes on climate is to:

  i) Maintain and develop *in situ* multiparametric long-term time series of observations measuring atmospheric and oceanic biogeophysical parameters as the ones defined by the list of Essential Climate Variables (GCOS-138, 2010).
  ii) Develop high-resolution global climate models able to better represent ocean processes such as mesoscale variability and convection.
  iii) Untangle the scale interactions. What is the contribution of each scale to the regional and large-scale transfer of properties? What defines the existence of preferential oceanic pathways, hence leading to high connectivity and property transfer, and what separates neighbouring regions, to the extreme of producing well differentiated regional ecosystems?

- **Improve our understanding of submesoscale processes and their role in the Earth climate.** Advection, mixing and enhanced vertical velocities associated with mesoscale (10-100 km) and sub-mesoscale (<10 km) oceanic features, such as fronts, meanders, eddies and filaments, are of fundamental importance for the exchanges of heat (Mahadevan, 2016), freshwater and biogeochemical tracers between the surface and the ocean interior, but also for exchanges between the open ocean and shelf seas, and between the pelagic ocean and the benthos. Mesoscale has received much attention during the last decades and the new frontier for the next decade is the understanding of submesoscale dynamics and its impact on climate. Variability of the meso- and submesoscale vertical exchanges and the partial return to the surface of subducted properties are poorly documented. Further investigation is needed to:

iv) Understand the physical mechanisms driving the interactions between meso- and submesoscale features.
v) develop and implement high-resolution observation systems both *in situ* and remote-sensing sensors such as coastal HF radars and upon satellite platforms (von Schukman et al., 2019).
vi) Use multi-sensor approaches to reduce noise and increase resolution and accuracy.
vii) Implement and validate high-resolution numerical models.

Advances in these challenges would allow the scientific community to observe, understand and predict the routes by which ocean heat, oxygen and carbon are transported horizontally and vertically, which is one of the key challenges to better understand the Earth's climate system.

- **Improve the parametrization of mixing in ocean models**. The details of how ocean processes at different scales interact and contribute to ocean climate are rather complex and still poorly understood, becoming a source of errors in ocean and climate models. For example, ocean currents exhibit an energy cascade from the large scales, where its energy is injected, towards the smallest scales, where it dissipates. This transfer of energy (as well as of other properties, including the biogeochemical ones) involves the fractioning of eddies into progressively smaller ones through processes that largely depend on stratification and rotation. In practice, present day computing power allows to track the dynamics of eddies in simple flows at Reynolds numbers several orders of magnitude smaller than the values found in oceans. Therefore, ocean models continue to rely in a conceptual artifact named (effective) eddy diffusion and viscosity. To further improve our parameterization of mixing in ocean models the following actions should be taken:

viii) Promote the interplay between advances in supercomputing (hardware, quantum computing and software) and advances in the simulation of ocean turbulence.

ix) Implement unstructured grids and develop high-order discretization techniques to reduce numerical errors.

x) Develop eddy viscosity and diffusion schemes that take into account the characteristics of the energy cascade in the ocean.

xi) Promote the acquisition of microstructure turbulence measurements to estimate dissipation rates and contribute to empirical parameterizations.

xii) Translate experimental evidence of interactions between small-scale turbulence and biogeochemical processes to geophysical model parameterizations.

During the following decades it is expected that theoretical advances, more powerful computers and more accurate high resolution *in situ* measurements will provide a deeper understanding of the energy and tracer cascades in the ocean. The key challenge, however, is to combine the new insights with improved observations in order to better parametrize ocean dissipation in global climate models.

3.3. Role of the biological pump in climate

The efficiency of the biological pump depends on many factors, including the physiology of individuals (e.g. plankton and micronekton), the dynamics of ecosystems (e.g. structure of communities and biogeochemical processes) and the environmental constraints (e.g. light availability, wind stirring and nutrient supply). Many of them are predicted to change as a consequence of the evolving climate dynamics. However, there are still profound knowledge gaps in the understanding of many of the physical-biological interactions that govern the efficiency of the biological pump, which includes the storing, transformation and transport of many biogeochemical properties. In particular, the roles of different biota in the chemical transformation of biogenic organic matter and its transport beyond the euphotic zone, and the spatio-temporal variations at the meso- and submesoscale along the water column and from the coast towards the open sea are still poorly explained.

- **Improve our knowledge of epipelagic processes.** Traditionally, it has been considered that two well differentiated types of planktonic communities inhabit the photic layer of the ocean depending on environmental conditions. When the water column is well mixed and inorganic nutrients are abundant, phytoplankton is dominated by large species (diatoms), which favours the export of organic matter, increasing the strength of the carbon pump (Eppley and Peterson, 1979). The other situation corresponds to the small-sized microbial community found in highly stratified and low nutrient conditions. Under these circumstances, the internal nutrient recycling limits the export of organic matter. However, these two scenarios are ideal extremes of a real continuum of situations that a complex and varied microbial community undergoes responding to the several scales of environmental variability. Many microbial organisms, especially the smallest ones (<20 μm), remain to be characterized, particularly in their function. In fact, the flows of matter and energy in the photic layer of the ocean are conditioned by the various modes of nutrition that exist in the marine microbial realm, consequently controlling the export of organic matter out of the photic layer. Moreover, zooplankton, a very diverse group that act as main intermediaries with the upper trophic levels, are also key drivers in the export of organic matter to deeper waters via pellet production and vertical migration, and can be relevant contributors to nutrient recycling in the photic layer. Thus, a more accurate estimation of export fluxes requires:

  i) Improving our knowledge of the response of the planktonic community in the photic layer to environmental variability, emphasizing the physical-chemical-biological interactions.
  ii) Progress in the identification of the organisms in the planktonic community, characterizing their functions and responses and / or adaptations to environmental variability. The improvements of the different omic approaches available as well as future new single-celled techniques will contribute to this advancement.

- **Exploring the meso- and bathypelagic domains.** The transport and transformation of organic matter out of the photic layer into the bathypelagic domain, where carbon is sequestered on sub-millennium time scales, is a complex matrix of biological, biogeochemical and physical processes that we are just beginning to decipher. Along with the solubility pump, this complex transfer of organic carbon to the deep ocean is a main mechanism for sequestering CO_2 from the atmosphere, thus providing the most efficient marine aid to slowing down global warming. Seven critical knowledge gaps of the meso- and bathypelagic domain have been identified:

iii) Lack of accurate measurements resolving the appropriate temporal and spatial scales of carbon processes such as respiration and chemoheterotrophic carbon fixation to balance the carbon budget in the deep ocean (see chapter 3.2)

iv) Lack of knowledge about the metabolism, degradation and transformations of surface-ocean originated particles as they sink, including the growth of prokaryotes, fungi and protists, as these processes might regulate the transit time of carbon from the surface to the deep ocean and thus, the timeframe of return to the atmosphere. This includes the identification and quantification of relevant genes in organic matter processing.

v) Scant information about the role of meso- and submesoscale features in the injection of suspended and dissolved organic carbon to the ocean interior, which is necessary to improve the measurement of their fluxes.

vi) Lack of knowledge about the mechanisms regulating the instances of microorganisms (inoculation) in fast sinking particles and how this affects their physiology and organic matter transformation capabilities, including the role of prokaryote decomposition of metazoan-transported matter.

vii) Lack of data about the transport of organic carbon, mainly in suspended and dissolved forms, and associated microbes from the surface to the deep ocean through deep convection in those regions where deep (e.g. North Atlantic Deep Water, Weddell Sea Deep Water) or intermediate (e.g. SubPolar Mode Water, Mediterranean Overflow Water, Antarctic Intermediate Water) water masses originate. The physico-chemical and microbiological (activity and diversity) transformations occurring during water mass formation (large changes in pressure and temperature in short time intervals) are basically unknown.

viii) Poor estimates of the contribution of active carbon transport to the biological pump, and accurate assessment of the biomass and identification of the species involved. In particular, it is necessary to discriminate the migratory and non-migratory organisms responsible for the deep scattering layers.

ix) Insufficient evaluation of the impact that changes in depth (i.e., pressure) have on the chemical conditions (e.g. deoxygenation, acidification, organic matter quality, trace element concentrations) on migrating species – its aggregation composition, functional diversity – and the overall ecosystem metabolism.

- **Understanding the role of the coastal region.** Coastal regions –including continental margins– play a key role in the cycling of organic matter. Despite covering <10% of the total ocean surface, more than 40% of ocean CO_2 uptake from the atmosphere (Muller-Karger et al., 2005) and more than 95% of oceanic burial of organic carbon (Duarte et al., 2005) occurs in the coastal domain. About half of coastal carbon burial occurs in blue carbon habitats (mangrove forests, saltmarshes, seagrass meadows (Duarte et al., 2005). In addition, coastal regions export nutrients, that fuel production in the adjacent ocean, and also export organic material produced in the coastal ocean and on land through several conduits (e.g. river runoff, upwelling filaments, intermediate and bottom nepheloid layers). Quantification of the global contribution of the coastal region to carbon sequestration is very challenging because of the high heterogeneity of the coastal domain, but arises as crucial for constraining the global ocean organic carbon budget. Three main issues are identified:

x) Need to estimate the transfer of organisms and materials from the coast to the deep ocean through canyons and its effect on the diversity and activity of bathypelagic microbial communities. The evaluation of natural and anthropogenic perturbations on this transfer requires a multidisciplinary effort that include geological, biological, chemical and physical approaches.

xi) Need to estimate the transfer of organisms and materials from inland waters (low oxygen, high nutrients, aged organic matter) to the ocean surface through submarine groundwater discharge and the effect on the diversity and activity of oceanic microbial communities.

xii) Need to estimate the contribution of blue carbon habitats (mangrove forests, saltmarshes, seagrass meadows, kelps and other seaweeds) to long-term CO_2 ocean sequestration, including *in situ* carbon burial in sediments beyond the habitat and carbon export to the deep sea.

- **Exploiting the insight from the paleo- perspective.** Instrumental records are crucial to understand ocean-climate interactions and feedbacks, but they are limited to only the last few decades. Paleoceanography makes use of a range of natural archives and indirect proxies to extend instrumental records further back in time. This allows studying Earth system processes for different configurations of the Earth, for example for periods in which the planet was globally colder or warmer than today, and with lower or higher concentrations of CO_2. Paleoreconstructions can provide very valuable insight on a number of processes discussed in this chapter, including the hydrological cycle, air-sea exchanges of CO_2, and the solubility and biological pumps. Regarding the latter, glacial/interglacial transitions are some of the most interesting targeted periods, since they involve natural changes in global temperatures accompanied by significant variations in atmospheric CO_2 concentrations. Some of the main needed efforts from this paleo-perspective include:

xiii) Determine the combination of oceanic mechanisms and processes that control past global atmospheric CO_2 concentrations on century – millennial time scales.

xiv) Develop multiproxy reconstructions of past changes of sea temperature and carbon cycle components (pH, pCO_2, export production and nutrient chemistry).

xv) Understand how the climate system operated during abrupt changes and time periods in the past which can be taken as analogues to present and future conditions.

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CHALLENGE 3

ABSTRACT

The sustainable management of marine life is essential for the well-being of present and future human generations as it plays a crucial role in the Earth's climate and biogeochemical cycles regulation, food security and coastal protection and provides many other goods and services of socio-economic and cultural value to humans. We identify the key scientific challenges where major research advances are needed to ensure well managed resilient living oceans in the coming decades from deep to coastal ecosystems.

KEYWORDS

biodiversity | pelagic | benthos | deep ocean | coastal | climate change | species interactions | fisheries | conservation | restoration

CHALLENGE 3

ACHIEVING A RESILIENT LIVING OCEAN

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1. INTRODUCTION AND GENERAL DESCRIPTION

Ocean life plays a crucial role in regulating the Earth's climate and biogeochemical cycles of carbon and other essential elements, contributes to food security and coastal protection and provides many other goods and services of socio-economical and cultural value to humans. The sustainable use of marine life is essential for the well-being of present and future human generations. This is clearly recognised by the United Nations Sustainable Development Goal 14 "Life below water" with the statement "The world's oceans – their temperature, chemistry, currents and life – drive global systems that make the Earth habitable for humankind". Achieving a resilient living ocean is thus an insurance for a healthy planet (Diaz et al. 2019).

The living ocean is vulnerable to human pressures and 66% of the ocean area has experienced cumulative and synergistic impacts (Diaz et al. 2019). In the coastal ocean, the extent of coral reefs has declined to half since the end of 19th Century (Challenges 5 and 7), one third of coastal vegetated habitats has been lost since World War II and other coastal ecosystems are suffering from pollution, eutrophication, hypoxia and global warming (Duarte et al 2020). The proportion of overexploited (33%) and maximally sustainably exploited fisheries stocks (60%) has reached a historical record of 93% in 2016 (FAO 2020). This means that both marine biodiversity is threatened and that fishing exploitation will be less profitable than it is today if the exploitation intensifies and expands further. The challenge of achieving sustainable fisheries production is complexified by the negative (in most cases) synergistic impacts of climate change on marine populations. Climate change may have a negative impact on marine ecosystem productivity that can be magnified up the food web (IPCC 2019). Aquaculture activities have kept on expanding primarily by generating environmental impacts due to the dependency on ocean-caught fish for fish feed, the outbreaks of disease from fish farms, or farm discharges and waste products.

Despite the unprecedented effort to understand the effects of cumulative human impacts on the ocean, there are still important limitations in basic and applied knowledge that need to be tacked with urgency if humans are to advance on achieving required sustainability goals. Biodiversity in many ocean habitats (from coastal habitats to the deep ocean, ocean seafloor, pelagic environment), and for many taxonomic groups, remains poorly explored or unexplored, which prevents us from having a complete inventory of marine life, and assessing the conservation status and the functioning of the overall living ocean. The availability and developments of new molecular tools, used in combination with traditional taxonomy, new technology (e.g. sampling equipment, remote sensing, vehicles, sensors) in addition to the advances in artificial intelligence and computing capabilities, can largely contribute to better explore the ocean biodiversity unknowns in the next decades.

Organisms rarely live in isolation, but as members of populations, assemblages and communities and, thus, they interact with others as a network. Inter- and intra-specific trait variation across marine species and species interactions are being increasingly recognized as fundamental to understand the spatial and temporal dynamics of population and community structure, functioning and resilience. However, our knowledge about the interactions that species establish, and the spatio-temporal changes of these interactions, is largely incomplete, which prevents us from having a good understanding of essential ecological processes and properties of marine ecosystems. New observational platforms, analytical tools and integrative modeling can substantially improve our knowledge and their full development, deployment and integration are key challenges for the future.

The risk of climate change impacts on marine ecosystems is projected to increase throughout this century, although it is expected to be much lower under the target scenario of greenhouse gas emissions required to meet the Paris Agreement relative to the business-as-usual scenario (IPCC 2019). To better anticipate the future of marine life we need to advance our knowledge on marine thermal ecology, as well as on other climate-derived effects (e.g. ocean acidification, hypoxia, sea level rise, ocean circulation) on marine communities, and the capacity of organisms to adapt to these changes. Moreover, synergistic or antagonistic responses of marine biodiversity to multiple climate change impacts need to be further investigated, along with how cumulative human activities play a role on marine productivity and biodiversity, on top of climate change.

There is growing evidence that recovery of threatened marine ecosystems is feasible and it can be achieved in the coming decades if pressures are removed or minimised and, when advisable, population recovery is catalyzed by interventions involving propagule supply of habitat-forming species (Duarte et al 2020). The global increase of MPAs promoted by the Convention on Biological Diversity can contribute to effectively managing marine biodiversity and thus MPAs are also instrumental to achieve a resilient living ocean. Overall, marine ecosystem conservation and recovery has been recognised as part of the ocean solutions proposed to reduce climate change impacts (Gattuso et al 2018) opening opportunities for climate change mitigation and adaptation strategies targeting marine biodiversity conservation and restoration. Eventually, achieving a good environmental status of our oceans requires the integration of human activities within the biophysical limits of our natural ecosystems and the re-thinking of the production, consumption and usage habits of the natural capital, living and nonliving, to make it sustainable (Raworth 2017).

Currently, there is a global plea, and in several places (e.g. EU, Canada, USA) a legal obligation, for stopping marine overexploitation and for establishing effective management plans to achieve sustainable fishing, rebuild stocks and preserve biodiversity while developing sustainable aquaculture activities. Making both fisheries and aquaculture activities sustainable requires large research and innovation efforts in many topics that go from new food technology, fisheries selectivity and gear innovation, climate change adaptation and mitigation all the way to stakeholder compliance and engagement. The achievement of Ecosystem-Based Fisheries Management (EBFM) poses serious challenges, including the fact that global fishing effort continues to increase with the large proportion of the catch that is not officially declared and the need to feed a growing human population (FAO 2018).

This chapter aims to identify the key research needs to achieve a resilient living ocean in the coming few decades, positioning CSIC research at the forefront of the marine science that is needed for a sustainable future (European Marine Board, 2019; Borja et al. 2020). This challenge requires integrative and beyond state-of-the art research, at least, along three main scientific pillars: 1) Improve our knowledge about biodiversity and functional diversity unknowns, 2) Determine how individual traits and species interactions contribute to community functioning and ecosystem resilience, and 3) Operationalize sustainable socio-ecological systems to prevent and mitigate the consequences of future global change but also to adapt to them and make the necessary transformations.

The urgency to address these research gaps in marine biodiversity is in agreement with the research prioritized in several International and European frameworks for the next decade, such as the UN Decade of Ocean Science, the UN Decade on Ecosystem Restoration, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services 2030 work program, the EU Biodiversity Strategy for 2030 and the European Green Deal. It is also important to consider the Sustainable Development Goals, SDOs (UN) specially the 14 SDO goal "Life below water", which the main objective is to conserve and sustainably use the oceans, seas and marine resources for sustainable development. It is worth noting that attaining a resilient living ocean cannot be approached without knowledge on the physico-chemical environment (see Challenges 2 and 5), cumulative human activities (see Challenge 4) and that management of marine resources to support human wellbeing needs a full consideration of socio-economic and ecological factors, their interplay and their governance (see Challenge 9).

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

A major challenge ahead is to fill the unknowns in marine biodiversity and ecosystem functioning. Taking advantage of the new capabilities to investigate unexplored habitats (see Challenge 1) and the new generation of molecular tools to speed up and automatize biodiversity research (see Challenge 8) should allow increasing knowledge generation in the near future.

Additional research is needed on the interactions and interconnections that exist within and between biodiversity assets (being genes, metabolites, species, populations, communities or habitats) to further establish the linkages between biodiversity and ecosystem functioning, the emergent properties of marine ecosystems, and the effect of multiple and cumulative human activities on them (see Challenge 2).

Major challenges to generate, interconnect and integrate our knowledge of marine life are ahead of us in the next decade, and include all aspects of scientific activities (from observational biology to complex modelling) with a clear vision on how to produce scientific knowledge to help the management, mitigation, adaptation and transformation of human activities on our Planet. In this regard, the scientific community is developing unprecedented capabilities of knowledge integration and transfer to support humanity to ensure well managed and resilient living oceans in the future.

3. KEY CHALLENGING POINTS

Below we describe the three key scientific challenges where clear advances are needed to ensure well managed resilient living oceans in the future: (1) Improve our knowledge about biodiversity unknowns, (2) Determine how individual traits and species interactions contribute to community functioning and ecosystem resilience, and (3) Achieve sustainability of the socio-ecological systems in that face of future global change.

3.1. Improve our knowledge about biodiversity unknowns

A key scientific challenge is to advance on the description of unknown biodiversity taking into account taxonomic, biological, ecological, habitat, and functional traits. The approaches to determine biodiversity at different biological complexity levels widely differ across groups. For instance microbial diversity assessments are fully dependent on molecular tools and molecular databases whereas those for other groups (e.g., zooplankton, metazoans, metaphyta) need to integrate morphological and genetic approaches and rely on availability of genetic databases and specimen collections. The discovery of unknown marine biodiversity will be driven by the development of molecular tools, the growth of genetic databases and the development of new observational platforms integrating a combination of static and mobile equipment to collect ocean information, including in situ sequencing, and with connections to satellites (see Challenge 1). Below, we list the specific challenges that need to be addressed in the coming years to significantly advance our knowledge on microbial plankton, zooplankton, metaphyta and metazoan diversity.

Unravelling the unknown biodiversity

Microbial plankton diversity

Microbes are ubiquitous in all marine habitats, represent main contributors to ecosystem biomass and activity, and are fundamental for ecosystem functioning and health. Marine microbes include a myriad of unicellular organisms of different sizes, cell organizations and trophic roles (primary producers, predators, osmotrophs, parasites, symbionts) and are central in trophic webs and nutrient cycles (Worden et al. 2015). Microbes play an enormous impact on human health and many biotechnological processes, and they will play a crucial role both in mitigating or amplifying global change impacts (Hutchins and Fu 2017). A complete understanding of the link between microbial biodiversity and ecosystem function, and its impact in biogeochemical cycles is essential both to assess the ocean's capacity in carbon sequestration and to better predict ecosystem responses in different future scenarios.

Although some ecologically relevant microbes have been isolated in cultures, most planktonic diversity remains uncultured. Given the minute size and inconspicuous morphology of most microbes, a full view of their taxonomic and functional diversity requires molecular approaches. The today expanding marine microbiology field is fully dependent on these approaches, which range from the use of community extracts to study the species present (metabarcoding), the genes present (metagenomics), the genes expressed (metatranscriptomics) or the protein content (metaproteomics), to single cell analyses such as taxa-specific microscopy and function, and single-cell genomics. Altogether, molecular approaches reveal which taxa compose natural communities, what is their genetic and functional potential, and which are the ecological and evolutionary mechanisms explaining the community structure and interacting networks.

Specific challenges in marine microbial diversity are:

- To retrieve ecological and biological relevant information from the massive sequencing data (see Challenge 8). Marine microbial reference gene datasets need to be standardized, with special emphasis on functional genomics, to assign a function to most of the unknown genes. Some of these genes might encode for new and useful compounds, opening promising avenues for bioprospecting. The achievement of this challenge requires the joint effort among scientists from different disciplines.
- To identify the genes encoding for biogeochemical functions, how does genetic diversity translate into functional diversity and how we can assign genes to specific functions when the microbes are not in culture. The possibility to reconstruct almost-complete genomes from uncultured microorganisms using bioinformatic tools would help to link genes with specific metabolic potential by reconstructing complete metabolic pathways of the unknown diversity.
- To scale single cell or community data to ecosystem function (see Challenge 2), including the potential of artificial intelligence to identify emerging properties from the big data generated (see Challenge 8). It is also fundamental to establish ecologically relevant model organisms, which can inform on the physiology and evolutionary mechanisms driving plankton diversity.
- To advance in our understanding of the multiple interactions and feedbacks among geochemical and microbial processes in the deep ocean (>1000 m, see Challenge 2).
- To understand the life histories of phytoplankton species, with focus on the resting stages in the sediment for meroplanktonic ones. Without proper knowledge of these resistance stages, we can hardly understand the dynamics of these species and other ecological aspects such as recurrence, dispersion or arrival of new species. Furthermore, as the phytoplankton group is characterized by small temporal and spatial scales, both in life cycles and in distributions, in situ real-time monitoring with a high-resolution sampling frequency is required.

Zooplankton diversity

Zooplankton is a broad taxonomic group, encompassing phylogenetically diverse organisms, ranging several orders of magnitude in size, and with very different life-history strategies. A deeper knowledge of the structure and diversity of this group is central to understand the energy and mass fluxes through it and to improve our comprehension of the actual functioning of the marine food web, nutrient recycling and global carbon cycle (biological pump, see Challenge 2). Within this large group, micoplanktonic grazers, including heterotrophs (microzooplankton) and mixotrophs (mixoplankton), are the primary grazers of phytoplankton in marine planktonic systems, accounting for approximately 60% of the pelagic primary production, and this group is responsible for a large portion of the transfer of matter and energy towards mesozooplankton (mainly copepods). Another zooplankton group, gelatinous zooplankton, is attracting increasing attention and becoming a relevant component of planktonic communities. Gelatinous zooplankton abundance has increased due to the imbalances of marine food webs resulting from anthropogenic pressures, such as overfishing and climate change. Moreover, the ability to explore and study large areas of the ocean until recently unexplored, such as the deep sea, has shown that abundance of gelatinous zooplankton is much greater than anticipated but the ecological role these organisms play in the ocean is still largely unknown.

Specific challenges in zooplankton diversity are:

- To know the long-term changes in the abundance and composition of zooplankton assemblages and their response to environmental and anthropogenic forcing. Although molecular techniques will increase the speed of data acquisition, they need to be combined with traditional approaches, particularly to quantify zooplankton biomass and for the taxonomic identification of many groups, in particular rare species, which can act as sentinels of subtle changes in diverse zooplankton assemblages.
- To improve our knowledge on the functional ecology and major ecophysiological traits (feeding rates, prey size spectrum, metabolism) of mesozooplankton and of microplanktonic grazers, including heterotrophs (microzooplankton) and mixotrophs (mixoplankton). New techniques, merging classic methods and modern molecular tools, need to be developed not only for exploring the diversity, but also for quantification of their abundance and biomass and for evaluating the trophic impact of these group.
- To understand the ecological role gelatinous zooplankton play in the ocean. This requires attracting specialists that can identify the species, advance our knowledge about pteropods, doliolids and pyrosomes, and

have access to specialized sampling and observation equipment (special nets, ROVs and submarines) required for their study.

- To understand the trophic relationships among the different groups of zooplankton in order to improve our comprehension of the structure and functioning of planktonic food webs.
- To investigate the early life stages of fishes (or ichthyoplankton) and of invertebrates, and the processes influencing their survival is a key issue for understanding both short and long-term variations in benthic invertebrates and fish population abundance. Many invertebrates and fish eggs and larval stages are planktonic and spend weeks to months in the pelagic realm interacting with pelagic predators and planktonic prey. Survival and dispersal during this vulnerable planktonic stage will influence the production and viability of adult populations as well as population connectivity. Physical factors, such as circulation, fronts and eddies, and environmental conditions that affect larval dispersal and concentration, together with biological factors, especially prey availability and predation pressure, are major controllers of larval survival. All these external factors have profound consequences for demographic connectivity and gene flow in invertebrates and fish populations that clearly affect how they may be conserved and managed, including the design and establishment of marine reserves.

Metaphyta and metazoan diversity

Several multicellular species are threatened with extinction, and some ecosystems are at the brink of collapse. So far, we only know a tiny part of the extant biodiversity in marine communities. Because we cannot protect or manage what we don't know, a huge and urgent effort to gather the much-needed knowledge on biodiversity patterns that lie at the basis of all management actions is needed before it is too late (Wilson 2004). This should be attained by integrating morphological taxonomic approaches with genetic (e.g. barcoding and metabarcoding) techniques. CSIC has an invaluable reservoir of taxonomic experts distributed across institutes, but most of these researchers are close to retirement or have limited time available for taxonomic work. At present, most CSIC taxonomists generate barcode sequences for their target organisms and they should foster and supervise an urgent and massive effort to fill the databases, in combination with the adequate logging of specimens in collections, and thus leaving their expertise embedded in genetic databases.

A specific challenge within this large group of species is to achieve adequate knowledge and a complete inventory of metaphyta and metazoan diversity. This should be approached by simultaneously supporting:

- To promote and enhance taxonomic expertise as a modern scientific carrier. This implies career opportunities for young people dedicated to integrative taxonomy and resource and logistics allocation to maintain and expand collections.
- To extensively use molecular tools to speed up integrative taxonomy.
- To deploy new observational techniques to allow overcoming the complexity of data collection in the ocean.

Ecosystem specific challenges

The pelagic ecosystem

The large variety of organisms that inhabit the pelagic ecosystem includes zooplankton and nekton species. The pelagic ecosystem is a vast region of the ocean and includes the epipelagic (to 200m depth), mesopelagic (200-1000 m depth), bathypelagic (1000-4000 m depth) and abyssopelagic (>4000 m) organisms. In general, life of the pelagic ecosystem is less known than the one found in demersal habitats, and the deeper the habitat, the less knowledge is available. Acquiring a comprehensive understanding of the biology and ecology of organisms inhabiting this vast ecosystem is a challenge for the marine scientific community. Most of the organisms of the pelagic ecosystem daily and seasonally migrate across the 3D ocean, and these migration movements are largely unknown.

The nekton group of the pelagic system includes large pelagic predators such as elasmobranchs (e.g. pelagic sharks and rays), teleost fishes (e.g. billfishes and tunas), large cephalopods (e.g. large squids), and marine mammals, sea turtles and seabirds. Some of these organisms have commercial value, but even more important is the fact that they play key roles in the structure and functioning of marine ecosystems exerting strong top-down control on smaller organisms. They also play important roles in demersal-pelagic coupling processes and in the transport of organic matter and nutrients in the water column (see Challenge 2). Despite the importance of these species, there is a general lack of information regarding their biological and ecological traits.

Pelagic ecosystems are also the habitat of many forage (fish) species, which include small and medium pelagic fish such as anchovies, sardines and horse mackerels and other small fish and invertebrates that are the essential prey components for large predators and also large contributors to global fisheries. Despite their ecological and socio-economic importance, many aspects of their biology and ecology remain to be investigated. Information about their movements, their response to environmental change and the impact of human activities (such as overfishing or pollution) on them is still far from being complete, despite the evidence that these organisms have strongly declined in many areas of the ocean due to the cumulative effects of global change. Due to their relevance for food security and ecosystem functioning, future studies that combine cumulative impacts on forage organisms will be key to understand the likely future trajectories of marine ecosystems and ecosystem services.

Mesopelagic organisms are ubiquitous and extremely abundant in the pelagic ecosystem and may be playing important roles as intermediate trophic levels linking top oceanic predators, which prey upon them, with zooplankton (primary consumers) that constitute their main food. The regular daily vertical migrations of mesopelagic organisms between meso- and epipelagic layers play a key role in carbon sequestration and thus climate regulation (see Challenge 2). Present knowledge of micronekton organisms inhabiting the mesopelagic realm indicates that this is a very diverse community, mainly composed of fishes, crustacean decapods, cephalopods and gelatinous organisms. However, we are far from knowing the actual number of species and thus their biology, ecology and functional traits. The lack of a complete biodiversity picture of this community is partly due to the difficulties of sampling at depth, and specifically discriminating against different layers of the water column.

A deep knowledge of diversity and biomass of the pelagic community is necessary to fully understand its role in active carbon flux through the water column, carbon sequestration and, therefore, climate regulation. In an overall scenario of depleted demersal fishing stocks, pelagic communities have been envisaged as a potential source of food supply. However, any attempt of exploitation of new resources requires a complete knowledge of the community, their functions, and an accurate assessment of the balances between the benefits of this exploitation and its effects on biodiversity conservation, global biogeochemical cycles and climate regulation.

Specific challenges in the pelagic ecosystem are:

- Seasonal and inter-annual spatial patterns of pelagic organisms are still partially or totally unknown and need to be described and quantified in

the future due to their relevance in terms of energy and matter flow in marine ecosystems.
- The interspecific relationships and feeding behaviours of pelagic organisms are only known in specific areas and there is no information about their temporal dynamics. In addition, the drivers of change are only partially understood. This information needs to be completed combining complementary methodologies such as stomach content, stable isotope and metabarcoding analyses.
- Many pelagic organisms are being impacted by cumulative effects of human activities, such as fishing and climate change. Advancing the integration of field observations, laboratory analysis and complex modelling will be key to understand the likely future trajectories of the pelagic ecosystem and its ecosystem services.
- In particular, mesopelagic organisms may play key roles in the ocean. To properly estimate their importance, it is first necessary to develop tools to accurately estimate their biomass, diversity and their interspecies interactions. The combined use of sampling gear and acoustic sensors is essential to obtain accurate abundance estimates of the variety of species involved (Irigoien et al., 2014). The integrated application of conventional taxonomic tools, barcoding and metabarcoding analyses will be necessary to obtain a complete picture of this component of marine biodiversity.
- Overall, the exploration of the pelagic ecosystem needs new sampling equipment to be developed, and it requires the development of new gear and technology, joint efforts of scientists and technicians, and intensive field sampling efforts with time-consuming and costly operations.

Benthic communities

Animal, plant and macoalgal benthic communities, from coastal (<50 m) to deeper sea (>200 m), provide key ecosystem services, since they act as nursery areas for species of commercial interest such as fish and crustaceans and play a paramount role in organic matter remineralisation, carbon sequestration and biogeochemical cycles. Coastal vegetated communities and coral reefs also help to prevent coastal erosion and impacts of sea level rise. Coastal benthic communities rank among the most impacted ecosystems by human action and, despite being accessible by SCUBA diving and to some extent by aerial and satellite imagery, a lot remains to be known about their structure, distribution and functioning. Still less known are the deeper marine benthic habitats.

In the last decade, technological advances have substantially improved our capacity to explore the seafloor and have changed our concept of benthic communities. The increasing use of systems such as acoustics, ROVs manned oceanographic submersibles, landing platforms for periodic *in situ* monitoring of environmental and biological parameters, along with the development of molecular tools, have collectively allowed the discovery of many habitats and species with different conservation status and the initiation of studies of functional ecology in deep-water ecosystems.

Specific challenges in the benthic ecosystem are:

- To know the diversity, structure and functioning of marine benthic communities of coastal, continental shelf and deeper-sea benthic habitats. This requires improving current technology, exploration capacities, particularly to access the sea-floor beyond 50 m – 100 m depth, and the development and use of molecular tools.
- To map the distribution and conservation status of benthic communities and to identify those habitats that are well preserved as well as those that could be recovered when managerial interventions are implemented (see key challenge point 3)
- To incorporate the links between biodiversity and function of benthic communities in ecosystem modelling exercises assessing past and future trajectories of marine ecosystems change. Benthos has been traditionally considered as a sink of pelagic production. However, benthic communities do not only play the role of a sink, because the whole benthic assemblage operates as a very active boundary between sea floor and water column. The benthic – pelagic coupling approach allows a better understanding of the role of seafloor biota in an integrated view of marine ecosystems.

3.2. Determine how individual traits and species interactions contribute to community functioning and ecosystem resilience

Species traits and multiscale patterns: movement, migration and behaviour

The role of inter- and intra-specific traits variation across marine species is being increasingly recognized as fundamental to understand population and community functioning and resilience. Individual traits, such as behaviour are identified as functional traits affecting processes as diverse as species co-existence, biological invasions, or the species' adaptation to climate change

(Sih et al. 2012). The challenge is to delve into the eco-evolutionary processes that favour the maintenance of between-individual differences in functional traits, and how they affect population resilience and ultimately ecosystem functioning. For that, the development of new monitoring technological solutions is required to provide new spatiotemporally-resolved data to understand the role of species in their ecosystems, their relationship upon the environment and the evolutionary factors, including anthropic impacts, that modulate behaviour, distribution and connectivity (Aguzzi et al., 2019).

Biotelemetry, stable isotopes, eDNA or high-throughput – omics, and novel individual-based modelling approaches and their integration will produce tremendous opportunities to address this challenge, particularly for commercially non-target or deep-sea organisms. Advancing on this will yield key knowledge to inform decision-making management processes (i.e. reality mining, dynamic MPAs, systematic management) that should better assure a healthy status of marine organisms at long-term scale (Hays et al, 2019).

Chemical communication among marine organisms

From the largest animals to microbes, communication is a fundamental characteristic of life. Chemical communication, in particular, underpins a wide range of fundamental biological processes, from predation to parasitic infection, symbiosis, inter-microbial association in consortia, and reproduction (Saha et al 2019). Seascapes of foraging, defense and reproductive cues, both underwater and in the air, have been shown to shape population distribution and dynamics of macroorganisms as diverse as seaweeds, corals, urchins and other invertebrates, fish, seabirds, turtles and seals. New research should address (i) the identification of active compounds either in isolation or as metabolomic footprints, (ii) the identification of the stage of different life cycles where chemical communication plays a key role, and how this is affected by global change, and (iii) deliberate use of chemical communication in sustainable aquaculture.

The ocean is also extremely heterogeneous at the microscale; microbes are exposed to a multitude of dynamical chemical gradients, while still being able to distinguish what could be called "messages in a bottle" released by other organisms. This chemical heterogeneity arises from diverse sources, including molecular diffusion across membranes, broken cells, and secreted vesicles with chemicals that are ultimately sensed by microbes. The research of cell-to-cell communication will bring a new understanding of microbial ecology beyond our current paradigm of bottom-up and top-down controls or competitive interactions. Results from this new field will also influence our views on the factors controlling plankton diversity and interaction, among others. Specific goals to address this challenge include: (i) To characterize chemical complexity in natural gradients, and development of methods to track signals as a tool in microbial ecology; (ii) to develop microdevices that expose microbes to multiple, controlled chemical gradients simultaneously, to obtain mechanistic knowledge; (iii) to quantify the microbial response to chemical gradients and understand the dependence of chemotaxis on the organisms' life stages; and (iv) to incorporate this behaviour into ecological and biogeochemical models.

Species' key responses to climate change

The anthropogenic emissions of greenhouse gases causing global warming, ocean acidification, changes in ocean circulation and stratification, sea level rise and hypoxia, are compromising ocean biodiversity and productivity. Species can live within a range of ambient conditions (e.g. temperature) defined by tolerance limits within biological activity changes. The assessment of the effect of climate change on marine biodiversity calls for knowledge on species environmental requirements to persist, their sensitivity and vulnerability to projected climate change and their capacity to shift phenology, to migrate across the 3D ocean, to acclimate, evolve and/or to adapt in pace with future ocean conditions (Poloczanska et al 2013), including average climate change and extreme events (e.g. marine heat waves). This knowledge is still missing for most marine species and key ecosystems.

Knowledge about the synchronicity of responses to climate change of different species within communities is also essential. Changes in phenology have emerged as a primary indicator of species responses to climate change. Marine organisms are particularly sensitive to climate-induced phenological shifts in plankton communities as recruitment success is highly dependent on synchronization of the larval stage with pulsed plankton production. Environmental processes that control the phenology of planktonic blooms may differ from those that influence reproduction, such as temperature and photoperiod. These different controlling mechanisms could disrupt the temporal synchrony of these events under climate change, with negative consequences for i.e. fisheries. Range shifts in species spawning grounds act to ameliorate the extent of these mismatches across mid to high latitude regions, indicating that species with limited dispersal capacity may be among the most vulnerable to this particular climate change impact.

Knowledge on species tolerance limits and responses of biological activity to climate change related parameters needs to be expanded across and within taxonomic groups as well as life stages. These could be obtained by performing manipulative experiments, from observations of impacts of climate extreme events on marine life and ecosystem monitoring programs as well as derived from species distribution models. Multigenerational manipulative experiments will be crucial to assess the species capacity for genetic or plastic adaptation to climate change. Moreover, the response of marine biodiversity to multiple climate change stressors acting simultaneously should also be investigated. The role of epigenetics on marine biodiversity responses to climate change should also receive attention.

Existing and new long-term monitoring of environmental and biological parameters need to be strongly supported as long-term observations are instrumental for the detection of climate change impacts and climate change attribution. Technological advances in observational power envisaged for the next years will multiply our capabilities to assess spatial and temporal changes in either active or passive organisms (see Challenge 1). High-resolution data in space and time will permeate the future of marine ecology research. Technologies based on satellite products, tagging, individual sensors and artificial intelligence will help improve the analysis of connectivity and population shifts in response to extreme events and sustained climate change-related changes. Monitoring of poleward migration, tropicalization or meridionalization of particular areas should be targeted. Citizen science should become a key tool in climate change research in order to increase observation power and social awareness (see Challenge 9).

Observation and experimental results and numerical modelling will improve projections of marine biodiversity distribution and ocean productivity under climate change scenarios. The development of more reliable 3D coupled biogeochemical models at higher spatial horizontal (mesoscale to submesoscale) and vertical (mixed layer, chlorophyll maximum) resolutions will help to assess climate change impacts on biodiversity functioning. To better understand and predict spatial changes, many direct (e.g. behavior) and indirect (e.g. species interactions, trophic effects) effects that cannot be tested under controlled conditions will need improved mechanistic models that reasonably represent dynamic processes involving species and life stages within the ecosystem.

Contribution of ecological networks to ecosystem change and resilience
Knowledge about the ecological interactions between organisms is fundamental for understanding the functioning of the entire ocean ecosystem. The connectivity patterns of networks can convey the complex associations between species or genes, and reveal specific features that can help to comprehend processes (e.g. energy transfer) or features (e.g. niches) and provide important information on specific characteristics of communities (e.g. specific network architectures) or species (e.g. keystone or hub species). Networks can also help to learn from emergent properties of ecosystems and to understand how resilient or fragile ecosystems could be and help determine species or genes with key functions (ecological or metabolic). For example, most biological networks are not random in terms of their connections and thus they tend to be resilient to the random removal of nodes (e.g. species or genes). Yet, the removal of highly connected nodes (hubs) may disassemble the network (Montoya *et al.* 2006) with possible consequences for the functioning of the ecosystem. The loss of species related to anthropogenic stressors in general tends not to be random and directed towards species that play key roles in the ecosystems and are unable to adapt to the respective pressure. If these species hold unique positions or functions within a network, the vulnerability of the entire network may increase. Thus, identifying what genes, traits/functions or species represent network hubs is critical for determining community stability. In the case of habitat-forming species (i.e. seagrass beds, macroalgal forests, coral reefs) the outcome of this disassembly could result in habitat loss and potential ecosystem collapse.

Only few ecological networks have been reconstructed for marine assemblages, and many ocean networks remain (at least partially) unknown. A key challenge is then to increase our understanding of ecological interactions among marine organisms, large and small, from different habitats (pelagic and benthic, coastal and deep). Marine habitats are often characterised by strong top-down interactions, where few species play a disproportionate role. Therefore, basic ecological studies that focus on community processes and interaction strength are critical in marine systems given that even simple two-species interactions can be highly complex with a series of direct and indirect interactions. In a changing world, the nature of these interactions themselves may be changing and long-term monitoring is critical to detect these changes. New technologies can also help in addressing this challenge. For example, High Throughput DNA sequencing can help generate correlation-based networks between microbial "species" or genes that represent hypotheses that should later be confirmed via microscopy or experiments. Nevertheless, association networks may reveal specific network topologies, shedding light on microbial or gene interactions as well as on the potential resilience of some ecosystems. Subsequently, other analyses can determine, for example, how many genomes contain genes defining a particular function, and if it is found that only one genome does, thus the associated species could be considered keystone, as its removal could have large scale cascade consequences in the ecosystem. Future networks will change and new interactions may appear.

During the next few years, it will become fundamental to increase our knowledge on ecological interactions in the ocean. Climate impacts may operate either directly, through effects on individual physiology (metabolic and reproductive processes), or indirectly, through effects on prey, predators and competitors, as well as on diseases, organisms or parasites. Given the ongoing global change, it becomes imperative to significantly increase our comprehension of the hubs or keystone species in ocean webs, since their local or global extinction could trigger effects that are difficult to predict. In addition, it is important to be able to quantify the amount of resilience of marine interaction networks in terms of species loss or invasions. Addressing these challenges will need multidisciplinary teams, with expertise ranging from natural history, ocean observation, ecology and evolution to genomics and big-data analyses. Similarly, addressing this challenge will require consolidated techniques, such as *in-situ* and *in vitro* observations, coupled to experimental approaches, and newer and emerging technologies, like massive parallel DNA sequencing, proteomics and Artificial Intelligence. The new deployment of artificial intelligence techniques and the capability to access large datasets of historical observations and predicted new conditions may be fundamental to advance our knowledge of future marine networks to come.

Ocean life as a process

The living ocean is much more than the inhabiting individuals, the communities and the resulting ecological network. Ecological networks and ecosystems depend on the way biogeochemical properties, such as nutrients and oxygen, and individuals themselves are transported within the oceans. Ocean currents and frontal systems will set the characteristics of the physical and biogeochemical environment, and will also define how well connected or isolated are the ecosystems. The physical environment becomes part of the living network, inspiring us to rethink what we understand for individuals and for life itself.

The classical view of living beings is substance-based: a living being as substance within some well delimited boundaries, characterized by a plethora of complex functions in some sort of apparent equilibrium. This standard view defines living beings as individuals, physically bound within some limited space where substance is organized and self-regulated, responding to external stimuli and evolving through growth, adaptation and reproduction. An opposite view is a process-based definition: life is the summation of all dynamic processes, leading to a homeostatic flux of properties in space and time (Nicholson and Dupre, 2018). Under this perspective everything is connected, there is no independence between life and environment: the substance continuously flows among all parts and the spatial constraint of a living being disappears. There may be regions that exhibit a high-degree of organization during some limited temporal lapse but even these regions fully renew their substance on time scales much shorter than the time scale this complex organization lasts. In the process-based scheme, the standard static view of a living being is just a single spatiotemporal frame in the continuous flux of processes.

Embedded in the process-based approach, we find the fluxes of matter, energy and, very specially, information. These three properties flow within one area and between adjacent geographical regions, creating complementarity and resilience, bringing about the complexity of life. The resilient living ocean becomes much more than a metaphoric phrase, it turns into reality. We could argue that the ocean is indeed the single truly independent living being, a self-contained infinitely-complex system that operates relying solely on solar energy. Switching from an individual-based perspective of life (where substance-made living beings interact with each other) into a process-based view (characterized by the continuous flow of substance, energy and information) can bring new light to our understanding of the complementary roles of every component and the complexity of the entire system.

3.3. Achieve sustainability of the socio-ecological systems to future global change

Conservation and restoration of marine life

Because pervasive marine ecosystem disturbances, conservation and restoration of ecosystems with salient provision of resources and services are essential to achieve sustainability and adaptation of marine socio-ecological systems to global change. Identifying and solving the current bottlenecks in actions to protect and restore marine ecosystems are crucial as they would allow rebuilding marine biodiversity in the coming decades (Duarte et al 2020). Moreover, this research is crucial to support the development of strategies for climate change mitigation, adaptation and transformation based on marine biodiversity conservation and restoration actions, such are Blue Carbon strategies for marine coastal vegetation (Nellemann et al 2009).

Protection measures are a first step of paramount importance for ecosystem conservation. MPAs are an effective spatial, ecosystem-based protection management tool and Member States Parties to the Convention on Biological Diversity (CBD) agreed to cover 10% of their Economic Exclusive Zones (EEZs) with MPAs by 2020. Some now advocate the need for 30%, or even 50%, of protection of the ocean. The implementation and effects of such protection targets is a key topic of research for the new years to come. One of the most common ecological effects of MPAs is that they harbor more biomass inside compared to outside, and this effect increases with MPA size or overall coverage. Furthermore, larger fish inside MPAs produce more offspring per unit body mass than smaller fish and spillover from this increased production of recruits can result in much higher yields for fishing fleets, because replenishment is much greater. Despite the clear ecological, socio-economic and wellbeing benefits of MPAs, there are several challenges related to their location, ecological effectiveness and management enforcement. These are key aspects that can constrain MPAs success and future work is needed to ensure that most of the too-small or uneffective MPAs that currently dominate the list of available protected areas can be expanded or improved to become fully operational.

The magnitude of recovery of marine ecosystems and key species achieved and the time scales involved are highly dependent on several factors including species-specific traits, population connectivity, community dynamics, and the level of reduction of exploitation, pollution and other pressures on marine life (Duarte et al 2020). Ecosystem restoration is defined as human-mediated interventions facilitating the recovery of degraded ecosystems by reducing environmental stressors and often including the seeding of propagules of habitat-forming species to catalyze ecosystem recovery. Ecological restoration of marine ecosystems is emerging as a viable approach to promote conservation and recovery and it has been successfully applied in several marine habitats worldwide, such as coral reefs, mangrove forests, seagrass meadows, salt marshes and oyster reefs. However, restoration methods, particularly those based on propagule seeding, should be improved in order to increase project efficiency.

Despite the costs of marine ecosystem restoration, it can yield greater returns in value for ecosystem services such as water quality, fisheries enhancement, carbon sequestration, coastal protection and food provision. Identification of the key factors constraining the success of ecosystem restoration and the assessment of recovery (or avoidance of loss) of ecosystem services achieved by a restoration project is an essential part of the process because it will provide feedback for improved restoration designs and approaches. The spatial and temporal dimension and challenges of the recovery of ecosystems services in restored zones should be assessed using observations and/or modeling simulations.

How restoration will make ecosystems more resilient involves identifying the approaches to improve the response of restored systems to disturbances and global change. For example, by identifying how the provenance and/or the mixture of genotypes of the material used in a restoration action improves restoration success or its resilience to warming, etc. The protection and restoration of pelagic communities and deep-sea habitats is much more difficult than that of demersal and coastal areas, and current initiatives are scarce due to their open and dynamic nature and limited accessibility. Innovative tools and solutions may come to contribute to this issue in the future as novel technologies, approaches and visions are developed. In the framework of a state of environmental emergency, the restoration of marine habitats requires new methodologies that help accelerate their recovery. Transpants of structural species as it has been successfully operated in terrestrial systems are an innovative and viable action in coastal and deep zones.

Tradeoffs between ensuring food security and meeting sustainability targets

The alteration of marine biodiversity through marine fisheries has wide-ranging effects on marine resources and ecosystem function (Pauly et al. 2003), including impacts on the wider socio-ecological systems. Despite numerous initiatives, major challenges and knowledge gaps still remain to ensure a sustainable use of the ocean (Claudet et al. 2020) and implement the EBFM, which aims to balance the conservation of marine resources and their sustainable use (Pikitch et al. 2004). EBFM should include the understanding of the trade-offs and synergies between fisheries and other marine-related human activities, and should consider climate change impacts. To advance towards an operational EBFM, there is a need for an holistic and transdisciplinary approach that addresses the issue of how to fully integrate outputs from ecosystem and food web models into fisheries management advice within a social-ecological and policy (regulatory) context. In parallel to EBFM, the Ecosystem-Based Aquaculture Management (EBAM) is also focused on the sustainable exploitation and good environmental status of coastal ecosystems. In this regard, research efforts to promote low trophic species (LTS) aquaculture, mainly macroalgae and molluscs, and to ameliorate the environmental impacts of finfish aquaculture through the Integrated Multitrophic Aquaculture (IMTA) are main research avenues for the next decade. The sensitivity of LTS, which are not fed by the farmers but by the environment, to climate change is also a main concern of LTS aquaculture and IMTA.

Several methods, data and tools are being developed to advance in this direction, but in many places, such as in European Seas, we are still missing a full operational framework and standardized protocol for the objective integration of quantitative and qualitative scientific evidence into decision-making processes. The operational framework can be adapted in different regional contexts to meet the need for sustainable fisheries, while promoting a BLUE Economy as set out in various policy instruments e.g. current EU Directives, such as the Common Fisheries Policy (CFP), Marine Strategy Framework Directive (MSFD), Marine Spatial Planning Directive (MSPD), the EU BLUEMED Research initiative and the UN Sustainable Development Goals (SDGs).

Achieving a Good Environmental Status of marine ecosystems

To advance towards a Good Environmental Status of marine ecosystems, there is an urgent need to change governance structures and integrate ecosystem considerations across multiple sectoral policies within a systemic approach. This implies to move towards an Ecosystem-Based Management approach (EBM) in a full understanding of the socio-ecological system and recognition that our resources are finite (Rockström et al. 2009), and they need to be used sustainably and fairly (Raworth 2017). This is a difficult task, and research will play a key role in successfully pushing this process forward.

To progress towards an EBM we need to master the development of cumulative effects assessments (CEA) of human pressures and environmental change. Many gaps remain regarding necessary information and methodological limitations (Stelzenmüller et al. 2020) and scientists will play a key role in filling the knowledge gaps. For example, in order to understand multiple, non-linear interactions and feedback between components of marine ecosystems and of human multiple activities, it is necessary to compile and analyse all available information with appropriate tools (see Challenge 2).

Numerical models that incorporate not only data but also our knowledge about the functioning of the ecosystems (or "digital twins") allow making predictions and scenario simulations of alternatives realities testing management options and helping with decision making (Tittensor et al. 2018, Fulton et al. 2019). We must strive to create the most comprehensive and complete "digital twins" of the real ecosystems taking advantage of the actual wealth of data and the big data coming ahead (see "Challenge 8"), as well as of the present improved computing capabilities. Seamless, scalable and interoperable digital twins of the ocean must help future assessments of cumulative impacts of marine ecosystems by integrating existing and future data-centres, technologies and infrastructures, and the new knowledge to come about ecosystem functioning (Fulton et al. 2019).

Digital twins of the ocean will empower a shared responsibility to monitor and ensure a healthy living ocean. They should allow assessments of ecosystems and habitats, the impact of human activities and forecasts of short and long-term changes, development of biodiversity conservation strategies, management of sustainable economic activities, assessment of infrastructure vulnerability and development of mitigation policies.

In addition, it is essential to include the impact of climate change integrative analysis to achieve EBM. The response of the marine environment to the combined effects of climate change and other human activities is context-dependent, ecosystem-dependent and species-dependent, which poses massive challenges ahead. Considerations of the land-sea processes and the key role that biological invasions play in marine ecosystems are also pending issues to incorporate. Large-scale collaborative studies and comprehensive modelling applications are needed to fill the current knowledge gaps.

The operationalization and integration of cumulative assessments into decision-making processes is yet to be seen due to their complexity and current limitations of knowledge and evidence to allow for the identification of human activities and pressures that should be reduced. Future developments in this direction will likely bring applications of Cumulative Effects Assessment (CEA) frameworks into real case studies, where there is a need to overcome the imperfect knowledge on the sensitivity of ecosystem components to distinct pressures, and to embrace uncertainty around the scientific evidence.

CEAs will play a key role into the decision-making process advising either specific policies, Marine/maritime Spatial Planning (MSP) and regulatory processes to move towards adaptive and proactive management processes within a "safe and just" operating space for socio-ecological systems (Raworth 2017). Future research on the effectiveness of management measures and how they can reduce the risk of negative impacts from cumulative effects is also needed to improve current practices. In order to correctly integrate CEA analysis into decision-making, science should be made clear, transparent and understandable to managers and stakeholders. Both a clear message and a straightforward assessment of uncertainty should be delivered to policy-makers to improve trust and usefulness of scientific knowledge. For this approach to become a reality, the involvement and efforts of both the scientific community and the stakeholders are needed. This is currently happening for some sectorial marine and maritime policies at EU level (e.g., Marine Strategy Framework and Common Fisheries Policy) but it is still necessary to engage more stakeholders and different scientific communities and to expand this approach to additional political and managerial issues.

Overall, multi- and transdisciplinary approaches, simultaneous observations of physical, chemical and biological variables at different time and space scales, and evaluation of past records are mandatory. It is also necessary to combine experimental designs (long term and short term) with *in situ* observations, and to develop complex models that integrate data, processes and scales, with the input and involvement of a broad range of stakeholders, and the mandate to inform real policy processes and develop future projections of change.

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CHALLENGE 4

ABSTRACT

The environmental state of the world´s oceans is deteriorating, as the rate, speed and impacts of changes are larger, faster and more imminent than previously anticipated. A myriad of stressors, including those derived from climate change, such as warming, acidification, deoxygenation, and others anthropogenically driven like eutrophication, chemical pollution or proliferation of undesired populations (pathogens, harmful algal and jellyfish, among others) impact the oceans. There is an urgent need to understand the effects of these multiple stressors on ocean health and the implications for human health. In this chapter, we present specific actions required to achieve "healthier oceans". The accomplishment of this challenge demands a multidisciplinary approach based on ocean monitoring, observation, experimentation and modelling, to assess physicochemical and biological environmental symptoms and to forecast the combined impact/s of the global stressors.

KEYWORDS

acidification | chemical pollution | de-oxygenation | eutrophication | biological invasions | warming

CHALLENGE 4

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1. INTRODUCTION AND GENERAL DESCRIPTION

Oceans cover 71% of Earth's surface and are under increasing pressures during the Anthropocene. These pressures are threatening their functioning as well as the services they provide to mankind, including coastal regions where most of the Spanish and world population live (see Chapter 7). Anthropogenic perturbations have multiple dimensions affecting the physical drivers, chemical composition, and ecosystem structure and dynamics, such as warming, acidification, deoxygenation, organic pollutants, plastics and heavy metals, habitat destruction, eutrophication, bursts of pathogens, harmful algal blooms (HABs), and jellyfish invasions, among others. All these pressures not only affect water quality and marine ecosystems, but also can have direct and indirect effects on human health and well-being.

As CO_2 emissions have exponentially increased during the last two centuries, especially for the last seventy years, mainly due to the massive use of fossil fuels, the atmospheric concentrations of CO_2 and the atmospheric inputs of CO_2 to the ocean have also increased (see Chapter 2). Ocean acidification (OA), the decrease in seawater pH as a direct consequence of rising dissolved CO_2 levels, induces a series of environmental and ecosystem changes at different trophic levels. Ocean warming, prompted by the amplified greenhouse effect, favors other perturbations, such as the deoxygenation of oceanic waters due to a decrease in O_2 solubility with a higher tendency to be outgassed from the ocean and an increase of stratification in the upper ocean that, in turn, reduces oxygen transport downward in the water column. Deoxygenation can also be concurrently caused by other processes such as eutrophication, particularly in coastal areas. The scenario of how oceans are evolving is even more complex. In addition to alterations directly driven by climate change, there are many chemical stressors occurring simultaneously, such as the inputs of a myriad of organic pollutants by rivers and atmospheric deposition, the increasing concentrations of mercury and other heavy metals, the exponentially increasing release of plastics and plasticizers, as well thousands of other emerging pollutants. Legacy persistent organic pollutants, whose commercial use was regulated decades ago, are still found in oceans as witnesses of our environmental past. Chemical perturbations can also be related to altered ecosystems states, with the paradigmatic example of the release of toxins by harmful algal blooms. The combined oceanic perturbation by these multiple modifications of the composition of seawater has never been addressed comprehensively.

Physical drivers associated to increased stratification, ocean warming, hydrodynamics alterations, and Ekman transport also stress the ocean in many directions, which are poorly understood. These physical conditions shape not only the biogeochemical cycles of carbon, oxygen, nutrients and pollutants, but also affect marine ecosystems. These direct and indirect anthropic pressures, and others such as fisheries over-exploitation, induce changes in the structure of food webs affecting the functioning of ecosystems at all levels, from microorganisms to top predators. Hence, the ocean in the Anthropocene may be entering a new era of physical-chemical-biological interactions that remain largely uncharacterized. This is so, in part, because so far most of the studies on stressors in the ocean have focused on one or a few of the potential stressors, and little attention has been paid to oceanic functioning and response under multiple stressor scenarios.

Ocean perturbations imply interactions between ocean and human health. These links include the contamination of seafood by organic pollutants and metals, ocean contribution to the spread of antimicrobial resistant genes, a decrease in air quality in coastal regions due to volatilization of pollutants and precursors of secondary marine aerosols, as well as emissions of primary aerosols containing toxins and pollutants, modification of marine ecosystem services (e.g. carbon sequestration), provision of dissolved oxygen, with implications for small scale fisheries, aquaculture, tourism and recreation, amongst others. Human health is increasingly dependent on healthy oceans, including the psychological benefits of healthy ecosystems on human well-being, issues that are just beginning to be explored and require truly multidisciplinary approaches.

Therefore, the overarching goal of this chapter is to address the current specific challenges necessary to achieve "healthier oceans", and is structured around two key challenging points, "Multi-stressor impacts and mitigation in the Ocean" and "Ocean Health is Human Health". The main objectives are: i) to understand the interactions between different stressors on the structure and functioning of ocean ecosystems at different levels, and to provide exploratory research on the mitigation of the undesired impacts, when possible, and ii) to address the interactions between the anthropic ocean and human health using a multidisciplinary approach.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Our scientific knowledge about the consequences of the multiple stressors impacting the global ocean is not uniform. Progress and effects for some of them, such as acidification, warming, and marine litter, are being extensively considered by the scientific community worldwide, whereas research on other stressors (e.g. deoxygenation) is less abundant and the prognosis of their potential evolution at different spatial and temporal scales is limited. Furthermore, the approach applied to understand anthropogenic impacts in oceans has most often dealt with one individual disturber (presence of organic pollutants, or acidification, or HABs) separately, with interactive effects left unresolved. Due to limitations in knowledge and strategy, our predictive capability on the state of the future ocean is still constrained. Ocean acidification, warming, chemical pollution and eutrophication are among the key perturbations that need monitoring in order to reach goal 14 of the United Nations Oceans Sustainable Development.

The traditional compartmentation of research that we face nowadays can be attributed to a number of factors linked to the increasing specialization of scientists and research groups, the intrinsic technological and logistic difficulties of holistic and comprehensive research efforts, and that international research programs are generally focused on a few of these stressors at a time. This is also reflected in EU and international legislations, which delineate thresholds for specific stressors, even in some cases, such as pollutants, to few compounds among the hundred thousands of candidates. In addition, these thresholds limits are not delineated considering biogeochemical and ecological knowledge. For other issues, such as jellyfish or HABs research and monitoring, understanding their response in a changing ocean may allow to link operational oceanography to both coastal and open ocean environments, thereby facilitating the prediction of future scenarios and mitigation of impacts. If the multi-stressor perturbation on the ocean has been largely omitted, so is how the health of the ocean affects human health and its implications. The assessment of multiple stressors on ocean health, and how a *sick ocean* affects human health, is certainly a major challenge for Science and Humanity, probably not fully achievable in the coming decade. It demands a multidisciplinary strategy to pave the path to fulfill this objective. Such approximation requires to address a series of sub-challenges for a holistic and comprehensive understanding of ocean and human health. Such effort should encounter the appropriate framework in a large research institution, as the CSIC.

3. KEY CHALLENGING POINTS

As mentioned above, the overall goal of "ocean health" is structured here in two key challenging points: "Multiple stressors impacts and mitigation in the ocean" and "Ocean health is human health".

3.1. Multi-stressor impacts and mitigation in the Ocean

The Atlantic Ocean and the Mediterranean Sea have received considerable attention regarding certain chemical stressors, such as ocean acidification and pollution, while other world oceans are still under-studied. In particular, with regard to **ocean acidification**, the North Atlantic has already experienced a marked pH decline due to the absorption of a considerable amount of anthropogenic CO_2, and changes in the circulation of water masses attributable to climate change have been also described. With the predicted emissions rates, acidification will cause that, in less than 40 years, 70% of its cold-water coral reefs located below 1000 m depth will remain exposed to an environment corrosive for their carbonate structures (Perez et al., 2018). These ecosystems are deep-sea sanctuaries of high biodiversity that extend from the Azores to Iceland, so acidification will impact at a high spatial scale. In addition, even though shelf seas still present high saturations of $CaCO_3$, the Intergovernmental Panel on Climate Change (IPCC) projects marked decreases in pH and, therefore, the future of our coastal ecosystems, which support a high biodiversity and play a relevant socio-economic role, is uncertain.

Oxygen is of paramount importance for life in our Blue Planet, as it is critical for all aerobic organisms and global biogeochemical cycles. Over the last decades, the ocean has lost 2% of its oxygen inventory (Schmidtko et al 2017) and this decline, the so-called **deoxygenation**, has become one of the main stressors directly associated to climate change (Schmidtko et al 2017). Model predictions for the coming decades show scenarios with slower ocean circulation, decreased mixing of the water column, and an increase in microbial respiration, all of them promoting a decay of oxygen levels. Oxygen decline and the expansion of low oxygen waters affect ocean biogeochemistry and impact all trophic levels in different ways depending on their oxygen requirements. Critical regions are those oceanic areas with naturally occurring low oxygen levels, the Oxygen Minimum Zones (OMZ), and coastal regions strongly affected by eutrophication. Low oxygen ocean areas will expand in the future in response to global change (Frolicher et al 2016). Specific targets to be addressed in relation to the triad deoxygenation, ocean acidification and warming are:

- To increase and improve ocean observation, monitoring and experimentation. This issue is crucial to understand the spatial heterogeneity of OA, deoxygenation and warming, in coastal, deep waters and shelf seas. Upwelling regions and high latitudes in the North Atlantic are especially vulnerable and demand a long-term observation program. The potential role of Mediterranean waters in modulating biogeochemical changes in the Atlantic eco-region should be also investigated, with special emphasis on OA mitigation thanks to the high alkalinity of Mediterranean waters (Flecha et al 2019).
- Use of paleo-reconstructions to extend observations beyond the instrumental records. Such approaches can help to assess the natural variability of ocean processes and to gain insight into the actual impact of global change.

Chemical pollution in the marine environment has exponentially increased during the last century in pace with economic development, particularly from nutrient inputs, heavy metals, hundred thousands anthropogenic organic chemicals, and plastics. The chemical pollution problematic is vast and requires a wide range of approximations and procedures depending on the chemical species. So far, no study has accounted for all the families of organic pollutants, and the discovery of new pollutants has increased thanks to novel approaches for suspect and non-target analysis. Still, the occurrence and structure of many chemical pollutants remains unknown, such as the fraction of anthropogenic carbon within the pool of total dissolved and particulate organic carbon.

The Marine Strategy Framework Directive (MSFD; Directive 2008/56/EC) established by the European Union (EU) compels the Member States to achieve Good Environmental Status (GES) of their marine waters. This directive required the development of several steps, to achieve or maintain the GES on the basis of several descriptors, e.g. among them marine litter, eutrophication, and contaminants. Especially relevant was the prevention of hazardous effects for marine organisms and humans by exposure to heavy metals, e.g. Cd, Pb, Hg, Ni and their chemical derivatives, as well as some families of organic pollutants, which are considered as priority substances in the field of water policy (DIRECTIVE2013/39/EU). Among these priority substances, some are also subject to international treaties. Mercury, which accumulates and biomagnifies in marine aquatic food webs, has special regulations. The Minamata Convention, signed by 128 countries including Spain, entered into force in 2017, seeks to reduce human exposure to Hg by reducing Hg levels into the environment.

Persistent organic pollutants (POPs) are regulated internationally by the Stockholm Convention. Its objective is to protect human health and the environment from POPs, with a protocol to add new substances as far as their environmental fate and effects are known, with this addition being agreed by the parties. Nevertheless, regulated chemicals are a tiny part of the total amount of pollutants. There are currently 300,000 synthetic organic substances in commerce, which include pesticides, herbicides, flame retardants, plastics and plasticizers, UV filters, pharmaceuticals, food additives, personal care products, sealants, etc. In addition, thousands of hydrocarbons are released to the marine environment as residues from the incomplete combustion of fossil fuels or oil spills (González-Gaya et al. 2019). Surprisingly, the occurrence and dynamics of pollutants in the marine environment has only been studied for a small fraction of anthropogenic chemicals, often due to the lack of appropriate analytical methodologies. Until now, little attention has been paid to detect the effects of the complex mixture of pollutants in the sea and to investigate the effects across the biological kingdom, from microbes to top predators (Cerro-Gálvez et al. 2019). This is an important weakness, considering that living beings, especially microbes, are the engines driving the biogeochemical cycling of carbon and other essential nutrients with implications in the climate and functioning of the biosphere (Vila-Costa et al. 2020).

Current estimates of plastic load in the global ocean are lower than expected by orders of magnitude (Cozar et al. 2014). The abundance of the smallest plastics (< 5 mm, microplastics and < 100 nm, nanoplastics) in the ocean has not been quantified and measurements in the deep ocean are very scarce. Resolving the ultimate pathways and fate of plastics is a matter of urgency as its presence in the ocean threatens marine fauna and human health. The impact of plastic pollution can be classified into three major groups: physical injuries (e.g., the entanglement of marine fauna in plastic), internal physical damages by polymeric particles, and toxicological effects of plastic additives and monomers, and / or by other chemicals adsorbed from surrounding waters (Llorca et al. 2014). In addition, plastic leachates, and atmospheric deposition of pollution, constitute a source of C for heterotrophic prokaryotes (Romera-Castillo et al. 2018, González-Gaya et al. 2019) that, at short or long term, may induce biogeochemical alterations related to the C and O cycles, thus influencing OA and deoxygenation.

Specific targets to be addressed regarding chemical pollution are:

- To foster collaboration between administrative and scientific communities in order to ensure coherence in the actions and guarantee the generation of valid and useful results to understand the ecological status of the marine environments, implement real ecosystem approaches, and therefore improve management. Reliable data on trace metals, either essential elements for biota, e.g. Fe or Co, or deleterious pollutants, e.g. Pb or Hg, are still very limited. Implementation of adequate sampling and analysis protocols to deepen our understanding of the sources and distribution mechanisms of these compounds in the oceans is both a priority and a scientific challenge. The GEOTRACES international program (http://www.geotraces.org) was created in 2003 to foster progress on the study of the global marine biogeochemical cycles of trace elements and their isotopes. This program is leading to considerable quality improvements in sampling and analysis protocols and is increasing the databases of metal distributions in the world oceans. However, this knowledge has still not been incorporated into many monitoring programs.

- Characterization and quantification of the pool of organic pollutants. To develop analytical techniques for the target, suspect and non-target analysis of organic compounds in seawater, sediments and food webs. Advances in the ability to identify pollutants of concern from the complex mixture of synthetic legacy and emerging organic contaminants in seawater would improve the assessment of their ecotoxicology, including effects at molecular level, thereby facilitating prioritization of toxicants.
- To progress in knowledge about biogeochemical transformations of organic pollutants and their bioaccumulation in marine food webs. Special attention should also be paid to metabolites resulting from degradation and detoxification processes, since some of them may result in higher toxicities than the parent compound. The influence of organic pollutants on the structure and function of microbial communities should also be studied, including assessments under realistic concentrations and hydrodynamic conditions such as small-scale turbulence.
- Occurrence and cycle of plastics in the marine environment by assessing: i) the ecosystem metabolism alteration due to floating plastic, that hamper oxygen exchange and light transmission through the water column. ii) Their inclusion in the aquatic food web through their ingestion by aquatic organisms, with assessment of their bioaccumulation factors, as their high accumulation potential (up to 1-million-fold increase) may also pose a risk to human health. iii) The relevance of plastic as a source and or transfer vectors for co-contaminants. Plastic litter is a source of chemicals that can lixiviate (Romera-Castillo et al. 2018). These chemicals can be monomers of their polymers, or additives. Some of these additives, such as the phtalates, have been found to present toxicity in human. iv) Impact of plastic, and its degradation and removal mechanisms. Plastics with sizes in the range of micro- and nanoplastics are a concern for the health of the oceans due to the lack of standard methods for quantification in the different matrices (seawater, sediment and biota). Hence, specific analytical methods need to be developed. Filling the gaps of information about aging, internal degradation, localization, etc. is crucial.

- Development of –omic technologies to detect responses at molecular level, with a distinction between lethal and a number of sub-lethal effects and to link these responses to impacts at individual, population and ecosystem levels. Incorporate the knowledge of not only dose-response but also how individual responses affect other organisms (response-response) within the food webs. To develop tools and approaches to better predict impact at the oceanic level, including the impact of complex mixtures.

Harmful algal species and their proliferations are a "case study" in the seasonal dynamics of the microbial communities of our seas, where particular species thrive causing occasionally noxious or toxic effects. Although HABs are natural phenomena, some events are the result of multiple stressors, specially eutrophication and natural or anthropogenically-driven habitat destruction or alteration (Garcés and Camp 2012). In turn, HABs become a stressor for the ecosystems by e.g. leading to low oxygen availability and producing a variety of toxins that affect different organisms and eventually humans. Extreme events of HABs are considered "hazards" and have been presented in the "Safer Ocean" challenge, but HABs can also impact ocean and human health. Specific targets are:

- To characterize the synergistic, antagonistic and / or additive impacts of key ocean stressors (warming, acidification, deoxygenation and chemical contaminants) on the development of HABs, at least, the recurrent ones.
- To understand the role of HABs as stressors in the marine environments. To conduct, based on the achieved knowledge, risk assessment and elaborate mitigation and adaptation plans for the impacts of HABs in the environment.

Jellyfish populations, particularly from the two phyla Ctenophora and Cnidaria, are relevant due to their great impact on the ecosystem and human health. Jellyfish have a great plasticity to cope with anthropogenic driven changes, as certain environmental conditions favor jellyfish blooms. First, jellyfish can survive in degraded habitats, such as contaminated waters or under deoxygenation, which are hostile for most other organisms (Richardson et al. 2009). Second, overfishing diminishes their predators and competitors on resources, as both small pelagic fish and jellyfish prey on zooplankton. In certain sub-basins of the Mediterranean Sea, a change in the frequency of the blooms of *Pelagia noctiluca* has been confirmed, which also proliferates in the North Atlantic. Additionally, a larger abundance and frequency of the blooms of *Cotylorhiza tuberculata*, *Rhizostoma pulmo* and *Physalia physalis* (Prieto et al. 2010; 2015) have been observed over the last 100 years in the Mediterranean basin. Thus, specific targets within this sub-challenge are:

- To disentangle the evolution of jellyfish populations under a warmer and acidified ocean by assessing: i) how global warming may expand the natural habitats of tropical jellyfish species towards Spanish shorelines and ii) the capacity of these organisms to tolerate the increase in dissolved CO_2 and cope with OA.

Even though the assessment of **multiple stressors** should be the ultimate goal in the study of ocean health, as this is the real current scenario of global environmental change, the current knowledge of the specific challenges is not mature enough to address directly the multiple interactions between stressors, and the specific sub-challenges listed above represent research priorities, as listed by many panels of international research programs. Specific targets related to a multiple-stressed ocean are:

- To understand and better project the impacts of global change on marine organisms and ecosystems. The combined impact of global stressors such as OA, deoxygenation, pollutants and warming, must be investigated to ascertain the nature of the interactions: synergistic, antagonistic or only additive. There is a need for laboratory and *in-situ* experiments accounting for the natural variability of these parameters in addition to the changing trends. In addition, the adaptation of marine organisms to OA has been mainly assessed through short-term assays focused on a single stage of the life cycle, whereas transgenerational plasticity conferring population resistance has been overlooked. One step forward is required through development of multigenerational experiments based on longer-term exposures over all life-history stages and across multiple generations and conditions. This strategy will lead to accurately understanding population response to the real combined impacts of future local (e.g. pollution) and global stressors and identify vulnerable and resilient species as well as disentangle phenotypic plasticity from genetic adaptation.
- Interactions of plastics with other stressors such as warming, eutrophication, OA, and other chemical pollutants. Once in the ocean, plastic litter or particles are colonized by microorganisms such as phytoplankton, bacteria and fungi, forming a biofilm which covers such particle, the so-called "plastisphere". Plastics support a structurally and

metabolically different community from those inhabiting the surrounding water. Therefore, plastic can act as a vector transporting species from one place to another, contributing to the introduction of non-native species that may become invasive. Those attached communities, together with abiotic factors such as light and temperature contribute to the degradation of plastics and additives in the ocean. Current research is focused on the identification and isolation of microorganisms in the plastisphere with the capability to hydrolyse microplastics and associated pollutants.

- Stress ecology: Scenarios of chronic exposure are sometimes underestimated because the toxic effects are not so evident at short- nor at long-term. It is crucial to understand how the stress produced by chronic contamination can affect the fitness of the species, their relationships with other species and the surrounding environment, as well as their processes of habitat selection. Stress ecology provides a vision of the chronic exposure effects on the changes in the habitat functionality. Moreover, it is important to identify not only the most sensitive organisms, but also the most vulnerable life stages to stressor exposures, as well as to identify realistic sentinel species.
- Need for more interdisciplinary ecotoxicological research taking into account the different stressors of the anthropic ocean. There is a need to integrate results from *in vivo, in vitro* and *in silico* approaches, and from local to global studies. Knowledge from biology, microbial ecology, environmental chemistry, physiology, toxicology, bioinformatics, modelling, etc. will need to be merged to improve our ability to predict effects at oceanic level in order to protect ocean and human health. Numerical modelling is not only necessary but of paramount importance in order to gain predictive capabilities. The models would need to include physical and biogeochemical processes and food web interactions.
- Development of plans of Prevention and Mitigation of HAB hazards based on the acquired knowledge of the diverse factors affecting bloom dynamics (e.g. parasite infection, turbulence disturbance on cell biology), and explore the role of pollution, and their impact on human economy and health.
- Comprehensive study of the simultaneous impact of warming, OA, organic pollutants and trace metals on the biogeochemistry and food web interactions in low oxygen coastal and OMZ ecosystems. This challenge demands an intensive observation and experimentation program to fill the existing knowledge gaps. Among these are the effect of

pH on the microbial degradation rates of organic matter, on the complexation of trace metals and the interaction of pollutants with organic matter, on the toxicity of organic pollutants and trace metals in low oxygen waters, and on the combined impact of temperature, decreased pH and low oxygen on the diversity of bacteria and archaea in these waters.

3.2. Ocean health is human health

Human health is dependent on the environment. This came to be of wide concern in the 1960s and since then the raising concern on environmental impacts has spurred legislation for water and air quality at the EU level, or globally under UN initiatives (for example the Stockholm Convention). A field of environmental epidemiology has been developed during the last decades, and it is now widely accepted that air, soil and water quality as affected by gases, particles and thousands of pollutants, have notorious effects on human health including a wide range of diseases, and even mortality. The current knowledge of how ocean health affects human health still suffers from a shortage of data. Luckily, ocean food safety monitoring is setting off alarms, as illustrated for instance in the control of phycotoxins that contaminate natural or cultured seafood by the European Food Safety Agency (EFSA). Nowadays, EFSA is also analyzing climate change as a driver of emerging risks for food and feed safety, including risks from natural phycotoxins and chemical contaminants in the marine environments. However, ocean health can have a multitude of direct effects on the health and well-being of humans, in coastal regions and beyond. Oceans and seas are also a source of benefits for humans (Borja et al., 2020): bathing waters, recreation, tourism, promotion of physical and mental health, positive effects on social relationships, medicines and healthy diet (e.g. omega 3 fatty acids). In the 21st century, society should understand that maintaining these benefits for the present and future generations requires to work for Healthy Oceans.

Specific sub-challenges are:

- To examine effects of pollutants present in commercial fish for human health: Hg concentrations in commercial fish (from aquaculture or fisheries) are often above EU thresholds for human consumption. Implications for human health need urgent scrutiny. Similarly, commercial fish contains many lipophilic organic pollutants with yet unknown impact.

- To investigate the links between decreased water quality in coastal regions and air quality of adjacent regions. This influence of marine systems on air quality can be due to volatilization of chemicals from seawater, the formation of sea-spray aerosols containing pollutants and *in situ* produced toxins, or the volatilization of precursors of secondary organic aerosols. Influence of this source of atmospheric pollutants on human health needs to be addressed.
- To better ascertain the social, economic, and ecologic effects of jellyfish swarms. Jellyfish swarms can interfere with aquaculture, fisheries activities and also with power plants, by clogging their cooling systems. Jellyfish proliferation represents a decrease in biodiversity of the ecosystem and has implications for the flux of carbon along the food web, as less carbon reaches the economically important upper trophic levels such as fish. Analogous effects are caused by HABs and require similar approaches. See also Challenge "A safer Ocean".
- Pathogens and antibiotic impacts. Aquaculture influences oceans and coastal areas by the release of pathogens form the cultured species and by the treatments that are used to fight against diseases (Lulijwa et al. 2019). These treatments can generate bacterial resistant strains that can harm wild populations of species living in the same ecosystem. These antibiotics can reach humans by the consumption of wild stock that live in the vicinity of the aquaculture installations. This will not happen in the cultured stock since by law all treated cultured species respected a withdrawal time before being sent to the market. Although sewage is normally treated in waste water depuration plants, a growing number of chemicals, drugs and human pathogens are being released into the marine environment without a strict monitoring of their consequences. eDNA studies and chemical analyses show the great impact that these unmonitored releases are causing on the marine environment, which can increase in the near future due to human population growth. Concerning human pathogens. there are many gaps in our knowledge. Moreover, monitoring the presence of all these factors and mainly of human pathogens can be used as an early warning of population habits and behavior. In the recent CoVid19 crisis, a base line of human pathogens in the ecosystem could have let us know changes that could help us understanding how these pathogens were being shed into the environment.
- To provide society with integrated indicators of the ocean status relevant for human health. We need to advance in the identification of sentinel and target species, parameters, biomarkers and biogeochemical indices

to be used as indicators. Persistent and extreme pressures can drive to species extinction and physiological adaptations; organisms can also react to these pressures by modifying their spatial distribution and/or temporal and dynamics patterns. Responses can occur at all trophic levels, from microbes to top predators. Given the complexity of natural systems, research on ecosystem indicators requires designing multifactorial experiments to assess the biological responses to multiple drivers interacting simultaneously (Boyd et al. 2018), but also the maintenance of time series for *in situ* examination of ecosystem responses to physical and chemical perturbations.

- Quantification of marine ecosystem services to human health. It is vital to consider the marine environment as one of the most important supply of valuable resources and services, which are key for human health and well-being, for providing seafood, climate moderation, CO_2 absorption, maintenance of oxygen levels, etc.

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CHALLENGE 5

ABSTRACT

A marine hazard is a potentially damaging event, phenomenon or activity in the marine environment that may cause loss of human life, social and economic disruption or environmental degradation. In the last 30 years, natural and human-induced hazards have caused over 1.6 million victims and the economic losses average 300 thousand million dollars per year. Marine hazards are amongst the most devastating ones. Here we present the research challenges we face as a society to achieve a safer ocean whereby human communities and the environment are better protected from the most outstanding biological, climatic and geological threats. We advocate for the implementation of a multi-hazard research strategy with emphasis on trans-disciplinary collaboration, development of improved observational infrastructures and data-sharing platforms, multi-hazard warning and management, and effective transfer of information to stakeholders and authorities to enhance impact mitigation.

KEYWORDS

natural and human-induced hazards

extreme | climatic events

biological hazards | geological hazards

identification and characterization

forecasting | impact scenarios

warning systems | impact mitigation

CHALLENGE 5

A SAFER OCEAN: TOWARDS MARINE HAZARD IMPACT MITIGATION

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1. INTRODUCTION AND GENERAL DESCRIPTION

As defined in the Hyogo Framework for Action of the United Nations Office for Disaster Risk Reduction (UNDRR), a hazard is a potentially damaging event, phenomenon or activity that may cause loss of human life, social and economic disruption or environmental degradation. Hazards can include latent conditions that may represent future threats and can either be natural (geological, climatic and biological) or induced by human activity (environmental changes and accidents). In contrast to gradual, large-scale processes affecting the environment at the long-term such as those described in challenges 2 and 4 of this Strategic Theme, hazards are often identified as being more local and infrequent, but intense (i.e. they display substantial deviations from mean environmental conditions) and/or severe (i.e. they result in significant environmental and socio-economic losses and/or human casualties). In the last 30 years, natural and anthropogenic hazards have caused over 1.6 million victims, and the average economic losses are close to 300 thousand million dollars per year (UNDRR, 2015a). Reducing hazard risk and losses in lives and health and in the economic, social and environmental assets of persons, businesses and communities through a science-based approximation is the expected outcome of the Sendai Framework for Disaster Risk Reduction (SFDRR) 2015-2030, endorsed by the UN General Assembly in 2015. This is reflected on the first three SFDRR priorities: 1) understanding disaster risk; 2) strengthening disaster risk governance to manage disaster risk; 3) investing in disaster risk reduction for resilience (UNDRR, 2015b).

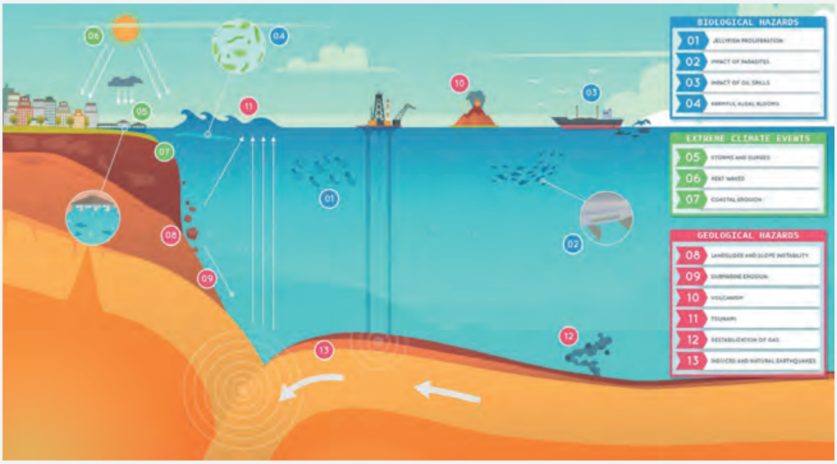
Marine hazards such as tsunamis, storm surges or harmful algal blooms, are of particular socio-economic concern in a changing world where 50% of the population lives within 100 km from the coastline, 70% of the megacities face the ocean, and over 1 thousand million people are related to marine activities. The health and productivity of the ocean are facing serious challenges not only due to natural forcings but also by the effects of direct human actions and indirect forcings driving Earth's climate to change (as addressed in challenge # 2. Ocean variability and climate impacts). Harmful episodes to human health derived from toxins or allergens steadily increase. Marine hazards affect the physical status of the ocean and also the biological realm, which is driven by the changes accounted for in the seawater and sediments. Some biological hazards (e.g. parasites or harmful algal blooms) also cause enormous damage to marine resources and to the conservation of marine biodiversity, with subsequent serious impacts on human health and economy.

In this framework, one of the key societal outcomes of the UN Decade of Ocean Science for Sustainable Development (2021-2030) is "to achieve safer oceans, whereby human communities and infrastructures are better protected from ocean hazards and where the safety of operations at sea and on the coast is ensured". The agenda of the Decade, in line with the targets of the UN Sustainable Development Goals 13 (SDG 13 Climate action) and 14 (SDG 14 Life below water), recommends accelerating actions to mitigate the effects of geological and climatic hazards, while contributing to reduce other impacts to the ocean and marine life caused by human activities (e.g. waste, nutrient and plastic pollution, underwater noise, as addressed in challenge # 4. Ocean Health). The achievement of these SDGs will be pursued by promoting ocean research, ranging from basic investigation to understand hazards in all their dimensions, development of integrated multi-hazard warning systems, and knowledge transfer to the society to improve risk awareness, assessment, prevention and mitigation. The development of effective multi-hazard early warning systems and preparedness for tsunamis and other ocean-related hazards based on scientific understanding and on systematic offshore observations is one of the four high-level objectives of the Intergovernmental Oceanographic Commission (IOC) of UNESCO for 2014-2021 (IOC, 2014), and it has also been identified as an ocean research priority by the European Marine Board (EMB, 2019).

While coastal areas are threatened worldwide by marine hazards, Spain is particularly affected because the about 8,000 km of coastline is exposed to multiple stressors. In Spain, half of the population lives near the coast, which is densely urbanized and visited by over 80 million tourists every year. As a result, coastal ecosystems are heavily stressed and modified, pollution levels are excessive, and coastal erosion is rapid and severe. Additionally, major natural hazards jeopardize its coasts, as dramatically evidenced by the 1755 earthquake and tsunami that caused near 100,000 victims, or by the recent Gloria storm that affected particularly the Mediterranean coast. Therefore, understanding, monitoring and forecasting marine hazards and efficiently transferring the information to the administrations and the society to mitigate the associated risks, stand as outstanding challenges for the future.

Rather than describing the achievements and the current status of marine hazard research, in this chapter we concentrate on the envisaged course of development of the CSIC research lines that, in our opinion, can help to fulfill the gaps of knowledge and make the most significant contributions to the overall challenge mentioned above. The chapter is structured in three key challenging points based on the nature of the risk: biological hazards, extreme meteo-climatic events, and geological hazards, both natural and anthropogenically-driven (Fig. 5.1). Although each event is distinctive, marine hazard-related research has several common aspects that must be jointly tackled to achieve the overarching goals. First, it is necessary to enhance coastal and offshore observations to better identify and characterize the sources of the hazard. Moreover, the models of event occurrence, forecasting and impact scenarios must be improved and fed with new observations, and multi-hazard warning systems must be developed and harmonized based on the knowledge of the associated risks. Finally, scientific knowledge and data must be incorporated into societal preparedness, emergency planning and risk mitigation actions.

FIGURE 5.1—Infographic illustrating the main biological (01-04), extreme meteo-climatic (05-07) and geological (08-13) marine hazards investigated at CSIC and described in this chapter. Design Investid Plus.



2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

With the overall objective of reducing losses in lives and risks to health and to the economic, social and environmental assets, the first priority of the SFDRR 2015-2030 is understanding disaster risks in all their aspects, from the knowledge of hazard source location and characteristics to the effective protection of people and assets (UNDRR, 2015b). This approximation requires the development and application of science-based methods for hazard mapping, monitoring, and modelling, as well as the improvement of observations and data-sharing platforms, in order to develop efficient multi-hazard early warning systems. These aspects, and particularly the development of the "ocean dimension" in an integrated multi-hazard warning system, are also in line with the research and development priorities of the Ocean Decade (Ryabinin et al., 2019). The three key challenging points described here respond to these research priorities from the expertise of the CSIC research groups. The expected research outcomes will have a profound impact on basic and applied ocean science at both regional and global scales.

The increase in quality and in the temporal and spatial sampling scales of water column and sediment observations will allow early detection and mapping of biohazards and marine heat waves. Repeated accurate seabed mapping will provide high-resolution information on seafloor relief and, in turn, on coastal and seafloor erosion and on transport processes. Combined with sub-seafloor imaging, it will also allow identifying and characterizing potentially hazardous geological structures, whereas long-term seafloor monitoring will provide invaluable information on their dynamic behavior. The availability of long-term, high-resolution multi-sensor data sets will also allow improving predictive models of biohazard evolution, impacts of extreme meteo-climatic events and of earthquake and landslide dynamics. Such a comprehensive marine data set will open new perspectives for big data analysis using artificial intelligence and data mining techniques to search for hidden multi-hazard correlations through new collaborative research. This, in turn, could help untangling intricate, poorly known cause-effect relationships of inter-related hazards (e.g. landslide and earthquake source models, tsunami generation and inundation scenarios). Accurate hazard source mapping, precise predictions of their spatio-temporal evolution and impact including explicit causal relationships, are all key ingredients to develop effective multi-component warning systems to be implemented at regional and global scales.

In summary, achieving these goals will have outstanding socio-economic benefits, as it will allow saving thousands of lives and reducing huge economic losses once a suitable technology for a multi-hazard warning system is implemented. Our research outcomes can be transferred to civil protection and stakeholders to raise awareness among coastal and offshore industries, public authorities and the society as a whole. Eventually, this research is intended to contribute to the overarching goal of effectively mitigating the impacts of multiple risks associated with ocean hazards.

3. KEY CHALLENGING POINTS

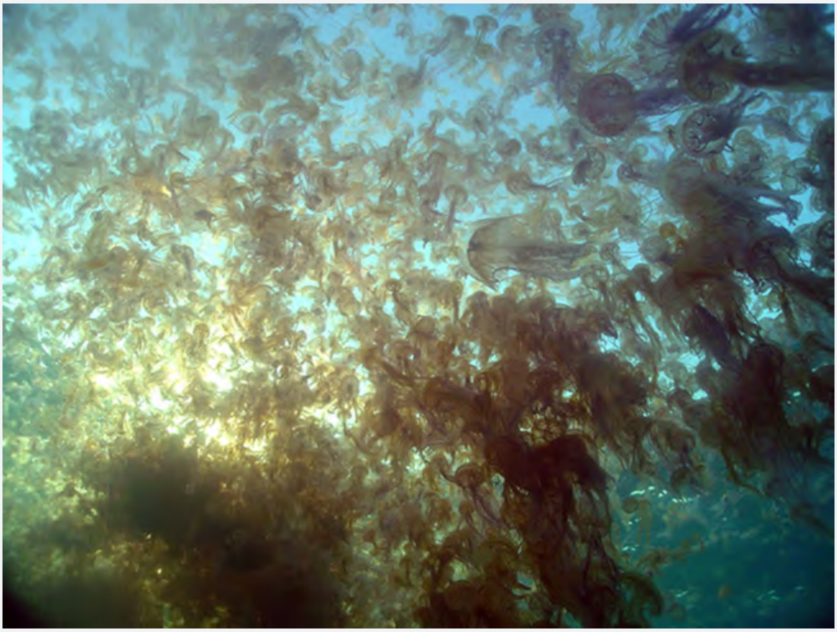
3.1. Biological marine hazards

Over the last two decades, there has been growing evidence on the importance of oceans for human health and wellbeing, as well as on the impact of different hazards. There is need to identify major biological risks to humans and oceans such as Harmful Algal Blooms, invasive species, jellyfish proliferations and pathogens (e.g. bacteria, viruses, and parasites), all impairing marine ecosystem services directly linked with human wellbeing (food, transport, energy, recreation, economy). Traditionally, some biological hazards arise from exposure to biogenic substances or microorganisms resulting from anthropogenic activities. For many years, microbial contamination of recreational waters represented a relatively well-known source of public concern. Conversely, the effects of other naturally-occurring processes such as bacterial and parasitic pathogens are less known, let alone how people with underlying diseases or inherent genetic susceptibilities may react to equivalent biohazard dose and route exposures. Currently, the two most promising research challenges are the development of a theoretical framework with interdisciplinary metrics, which integrates and models oceans, biohazards and human health, and the development of long-term monitoring programmes to detect, identify and assess the exposure to marine biohazards with a broader scope. Multidisciplinary and holistic perspectives are needed to understand the cumulative impact of global warming and anthropogenic drivers on the hazardous role of biogenic aggressors of oceans and seas.

People are exposed to environmental parasitic pathogens through different pathways, including direct contact with or ingestion of infected seawater (with *Entamoeba*, *Giardia* or *Cryptosporidium*) during work or recreation, and are also affected by consumption of seafood species infected with histozoic parasites. Among the most relevant are the zoonotic anisakids, which are driving serious problems to some of the most important fisheries worldwide due to product rejections related to quality and warmth. A challenge in determining potential risks from eating contaminated seafood is the uncertainty involved in zoonotic exposure assessment. Depending on the nature of the exposure and the characteristics of the populations, this susceptibility leads to health effects, which in turn have socio-economic consequences. Concerning marine parasites, it is well-recognized the existence of a “dirty dozen list” of protozoan and metazoan parasitic species in the edible parts of commercially-valuable seafood species, with the potential to spillover into people, with many other novel species still pending of questions raised on the risk they pose to humans. Some of them have already been included in the top ten of an expert opinion-based risk ranking framework obtained by applying a weighting scheme to all factors (from environmental to host circumstances) resulting in their transmission (Bouwknegt et al., 2018).

Understanding the etiology of injury or illness of the numerous and diverse parasitic species in an environmental health context requires investigating the social, ecological and biological origins, pathways, and mechanisms

FIGURE 5.2–Jellyfish bloom of the species *Pelagia noctiluca* in coastal waters of Ibiza (Balearic Islands) in July of 2013. Image from Project Medusa (ICM-CSIC).



leading to illness or injury. The necessity of an ecosystem-based approach is amplified in a rapidly changing ocean, also considering that parasites are small players but with crucial roles in all marine food webs (Marcogliese, 2004). The "one health" approach envisaged and implemented by the World Organization for Animal Health (OIE) and the One-health European Joint Programme (EJP) summarise the idea that human health and animal health are interdependent and linked to the health of the ecosystems to which they belong. This is a sustainable framework for an integrated community of research groups including reference laboratories in the fields of life and veterinary sciences, medicine, food sciences and environmental sciences. The idea behind the scene is that all zoonotic parasites occurring in marine ecosystems must overcome a hierarchical series of barriers to cause spillover infections in humans. Understanding how these barriers are functionally and quantitatively linked, and how they interact in space and time, will improve our ability to predict or prevent zoonotic events as a result of ecological, epidemiological and behavioural determinants of pathogen exposure and the within-human factors that affect susceptibility to zoonotic parasitic infection. State-of-the-art technologies incorporating multi-omics and ecosystem/epidemiological modelling using long-term, large-scale traceable data sets are essential.

Jellyfish blooms and massive beach arrivals have enormously increased in recent years. Thus, the frequency of these events and the periods of maximum proliferation are shortening. Among other reasons, climate change and overexploitation of marine resources are promoting and maximizing these effects. Over the last years, jellyfish blooms have generated a high environmental and socio-economic impact in human activities, such as access limitations to beaches, tourism decline, collapse of fish farms, collapse in the cooling systems of thermal and nuclear power plants in coastal areas, and problems at sanitary level due to jellyfish sting effects in human health. These years may be considered as catastrophic and will require innovative measures of prevention and mitigation that should be based on a rigorous scientific approach, including knowledge of the biology of the species and their capacity of reaction to major environmental changes. The bottleneck for this approach is to have and, above all, maintain long-term series giving precise information of temporal and spatial fluctuations of jellyfish blooms in coastal areas, such as the one being carried out in Villefranche-sur-Mer in France and the one in Catalonia in Spain, in addition to having specialists in the biology of jellyfish.

Harmful Algal Blooms (HABs) are proliferations of toxic and/or noxious microalgae and cyanobacteria that cause negative impacts on aquatic ecosystems, coastal resources, and human health. HABs can be approached from different perspectives, either as hazardous events or in relation to ocean health. These events, which can be both extreme and emerging, recurrent and even predictable, are caused by different species with diverse physiological commonalities. Under certain circumstances, some microalgae reach high cell concentrations affecting the ecosystem and disrupting food web structures. These high-biomass blooms may decrease the water quality of coastal areas, negatively affecting tourism and recreation activities. Some microalgae are specifically involved in massive mortalities of wild and cultured fish, causing economic losses on fisheries and aquaculture. Other algae produce chemical compounds that are toxic to marine fauna and to humans, either by direct contact and aerosol exposure or by ingestion of contaminated seafood. Different biotoxins (saxitoxins, domoic acid, okadaic acid, spirolides, azaspiracid, among others) are bio-accumulated by shellfish and other marine organisms and transferred through the food webs to wildlife and humans that become intoxicated after ingestion of the toxin-contaminated seafood.

HABs occurrence depends on the interactions of biological, physical and chemical factors that operate at many different spatio-temporal scales. Although some events can be considered natural phenomena, human activity in coastal zones is promoting blooms through eutrophication, ballast waters, species translocation or habitat modification. Furthermore, climate change appears to favour the biogeographic expansion of some harmful species, causing unexpected extreme toxic and massive events worldwide. Overall, HABs may increase in the future and their impacts may intensify.

Harmful algal species and their proliferations are a "case study" in the oceanic seasonal dynamics of the microbial communities, where particular species proliferate and cause occasionally noxious effects. By investigating these special cases, we advance in the understanding of several aspects of phytoplankton ecology. Overall, the knowledge gained in algal culturing and metabolism could be potentially applied in obtaining pharmaceuticals and nutraceuticals from algae, biotechnological applications, biofuels production, environmental clean-up, and development of nanotechnology (biosensors).

The challenges ahead include the development and implementation of HABs monitoring and early-warning systems allowing to predict and detect early stages of bloom development, thus facilitating risk assessment and adaptation measures. Monitoring requires new technologies with finer spatio-temporal resolution and should be integrated into multi-disciplinary ocean observation systems. Improving the understanding of the complex biological and ecological mechanisms modulating bloom occurrence is also crucial, in particular microbial and environmental interactions through the integration of new approaches and disciplines. This knowledge, along with a better characterization of the HABs effects on the economy and human health, will allow designing plans to prevent and mitigate HABs impacts.

Most contaminant spills have not a biological origin, but their consequences can affect very intensively the ocean biological realm. Oil spills at sea, in particular, are hazardous events typically caused by a combination of human factors and meteorological conditions. The most catastrophic spills in Spanish coasts occurred accidentally by failures in downloading facilities and emergencies combining poorly maintained tankers and bad weather conditions, particularly offshore Galicia from 1970 (Polycommander, Urquiola, Andros Patria, Casón, Aegean Sea and Prestige). Oil spills are also introduced in the marine environment in a diffuse way, commonly associated with illegal operations of bilge cleaning along shipping routes. Although quantities are not equivalent to those of massive spills, they are continuous in time. Their impact is unknown given the difficulties to detect them and know the amount and composition of the products released.

When spills reach coastal areas, the affectation on littoral ecosystems is devastating, producing important economic losses and social impact. As zero risk is unattainable, the main challenge when a spill is produced is detecting it rapidly using satellite, radar and drone images and AUV tracking. Oil signatures in near infrared and visible bands through multispectral scanning can complement the coverage limitations of radar images. Furthermore, improved models of coastal circulation are necessary to trace the evolution of spills and predict trajectories (e.g. Project ESEOO, Establecimiento Español de Un sistema de Oceanografía Operacional). New approaches to better understand the geometry of oceanic flows are needed to better interpret the fate of spills. Also, it is important to develop tools to advise authorities taking immediate decisions. The reanalysis of historical data of weather and ocean fields are now accessible at the European scale through the Copernicus marine environment monitoring services. This will allow computing beaching probability maps of affected coasts, which combined with better estimates of the physico-chemical characteristics and the microbiological and photochemical reactivity of oil, may help risk assessment and preparedness. Regarding the impact on ecosystems, the accumulation of crude oil causes the most significant effects. It is essential to create efficient protocols to confine spills and to remove the insoluble oil phase. The next step should be bioremediation. The interaction between microbial species reveals as the most appropriate tool for oil biodegradation that remains buried or adsorbed in the sand (McGenity et al., 2012). Coupling with these recommendations will improve the negative impact of oil spills on marine resources and even over emblematic vertebrate animals that can represent concern for the conservation of marine biodiversity, such as seabirds, turtles or marine mammals.

3.2. Coastal extreme meteo-climatic event-related hazards

Coastal hazards caused by extreme short-term (heat waves, extreme storms) and long-term (erosion, sea-level rise) events impact upon infrastructures and economy of coastal communities and industries, and produce non-monetary issues such as loss of human life, the social well-being, the cultural heritage or ecosystem services. Disasters caused by weather and climate-related extremes in EU Member States amounted to 426 thousand million euros over the 1980-2017 period (EEA, 2019). In the future, only considering hazards related to sea-level rise and storminess, such as coastal flooding and erosion, it is estimated that in regions with low-lying coasts they can produce losses amounting to several percent of GDP by 2100 (IPCC, 2019). The increase of coastal hazard impacts during the last decades is attributable to the larger exposure of people and assets and to climate change. The influence of climate change in the increasing frequency and intensity of extreme events is well-documented for some of them (e.g. sea-level rise, heat waves). The attribution of storms or small-scale events to global change, however, is more difficult and constitutes a research challenge known as "attribution science", which uses observations and models to identify the factors that govern extreme climatic events (Schiermeier, 2018). This topic is a priority under the Marine Strategy Framework Directive, but research on extreme meteo-climatic events requires improved monitoring methods and solving important scientific gaps in the knowledge of the onset, forecast and impacts of extreme events. Here we develop different aspects related to these general topics.

Marine Heat Waves (MHWs) are "periods of extreme warm sea surface temperature that persist from day to month and can extend up to thousands of kilometers". The mean duration and frequency of MHWs have increased significantly over the past century, and they are expected to keep increasing. They have severe impacts on marine ecosystems health and productivity (Smale et al. 2019). For instance, there is evidence of increasing mass mortality events on macro-benthic species in response to MHWs. Just in the Western Mediterranean Sea, moderate to strong MHWs during summers of 1999, 2003 and 2006 affected more than 50 macro-benthic species along the coasts of Spain, France and Italy. MHWs research has two main challenges in the years to come. First, improving our understanding of their propagation in subsurface layers. At present, MHWs studies are based on the analysis of satellite sea surface temperature data. However, the linkage between surface MHWs metrics and the conditions in the water column is not straightforward, due to seasonal stratification and to the influence of wind on coastal hydrodynamics. This hinders our understanding of the related ecological impacts. To face these issues we must develop remote-sensing observing systems to track the evolution of MHWs and to improve temperature monitoring in coastal areas as well as offshore. Second, we must develop early warning systems. The reliability of these systems will depend upon our ability to track MHWs in near real-time conditions and on their influence on marine ecosystems. For this, we need to improve our ability to define thermal stress responses of key ecosystem components by coupling the monitoring of in situ temperature with the monitoring of ecological indicators in coastal areas, and by obtaining experimental thermal stress response functions on ecosystem foundation species (including inter- and intra-population variability).

A storm surge is the sea level rise caused by the accumulation of water in the coast produced by wind-generated currents. Extreme storm surges are a severe threat in coastal areas as they may cause loss of life and large economic and ecological damage. Strong storms, together with low coasts with large shelves will suffer the most dramatic effects under coastal flooding, depending on its timing relative to the tidal cycle. The most dangerous storm surges are those produced by long-lasting storm systems that coincide with spring tides. In addition, storm surges tend to occur together with other potentially hazardous factors, such as waves and rainfall. In the long-term, global warming is predicted to favor the intensification of extreme surges, although there it is still unclear whether this signal can be detected by observations. The combination of extreme surges with sea level rise and larger river volumes by rainfall will increase coastal flooding during the next decades, so a huge effort for the coastal adaptation and mitigation of damages is required. Thus, the main challenge we face is improving regional and local models of extreme storm surges based on detailed topo-bathymetries and hydro-dynamical models coupled with the atmosphere, to forecast coastal impacts and to develop real-time early warning systems. Accounting for compound extreme events also requires detailed coastal monitoring, the improvement in atmospheric models and the technological development enabling monitoring with finer spatial and temporal sampling. Additionally, nature-based strategies for storm surge-related damage mitigation need to be further developed.

Coastal erosion at sandy coasts can be defined as the process by which strong wave action, storm surges resulting from storm events, river floods and/or sea level rise carry away soils and sands along the coast (Mentaschi et al., 2018). Storm-induced erosion in combination with projected mean sea-level rise may lead to enhanced shoreline retreat and, consequently, to increased coastal exposure and vulnerability. Given the paramount role of the littoral zone in almost any kind of human activity, reducing the impact of the coastal erosion related to extreme events is a great challenge. From the perspective of dynamic modeling, wave and sediment dynamics, observation systems, and climate and sea-level rise, the improvement of decision-making in coastal management requires undertaking urgent actions. First, it is necessary to improve our understanding of past events and the coastal responses by producing higher-resolution databases of marine events and coastal response reanalyzing satellite and video-monitoring products. It is also important projecting long-term conditions of marine extreme episodes and mean sea-level at the coastal zone and improving the understanding of the dynamics of sedimentary cells at different time-scales. Finally, we need to translate forcing factors and dynamical responses into impacts on assets and populations aiming at public awareness and at the design and implementation of effective adaptation plans.

Mean sea-level rise due to global warming is one of the major threats for many coastlines and coastal plains around the world. Projected scenarios of global mean sea-level rise at the end of this century provide a median range of 0.4-0.6 m for a mild scenario (<2°C) and 0.7-1.2 m for a warm scenario (4.5°C). An increase in frequency of coastal lowland flooding and/or erosion of sandy beaches is expected. Some of these environments constitute invaluable ecological reserves, and they hold resources of great economic value that would be seriously damaged. Key coastal areas are very extensive (see challenge # 7. Coastal oceans) and therefore particularly vulnerable and sensitive. Processes underlying mean sea-level variability include melting of ice sheets and glaciers, changes in land water storage and in the geoid due to surface mass load redistributions, glacio-isostatic adjustments and steric components due to changes in water density and circulation. The spatial and temporal patterns of sea-level variability are inferred from instrumental observations at tide gauges and satellite altimetry, and proxies of the geological record during post-glacial meltwater pulses and sea-level rise. Projected changes are based on physical numerical models, semi-empirical relationships, probabilistic assessments, or their combination. Having better predictions is a challenge requiring a number of improvements. These include the continuous monitoring of sea-level variability, especially at coastal sites, and anticipating mean sea-level changes using regionalized projections that serve as inputs for adaptive solutions in coastal management. We should also identify the most vulnerable coastal areas for which the adaption strategies (abandonment, retreat or protection) need to be defined. Finally, we should improve our understanding of past analogue periods of rapid mean sea-level rise to project on coastal evolution under changing climate forcing, and that of the impacts of sea-level rise on coastal ecosystems.

3.3. Geological marine hazards

Marine geological hazards affect the offshore and coastal environment, damage submerged and coastal infrastructures, and are the natural disasters causing the largest number of victims (Camargo et al., 2019). Major marine geohazards include tsunamis, offshore earthquakes, submarine landslides, gas hydrate dissociation, seabed and coastal erosion, volcanic eruptions, and flank collapses. Their distribution, frequency, magnitude and coupled effects define their destructive capability. In the twentieth century, tsunamis caused by offshore earthquakes, eruptions and submarine landslides killed over a million people, whereas in this century, the tsunami triggered by the 2004 Sumatra-Andaman earthquake alone caused over 230,000 fatalities. The economic losses caused by marine geohazards amount to billions euros and they constitute the main natural threat to offshore and coastal critical facilities worldwide, as evidenced by the inundation of the Fukushima nuclear power plant by a giant tsunami caused by the 2011 Tohoku-Oki earthquake. The Iberian margins and the Mediterranean basin are also vulnerable areas with a long record of destructive impacts (over 20 in the last century), including the 1755 Lisbon earthquake and tsunami, one of the most devastating catastrophes having ever occurred in Europe.

Despite decades of efforts and significant investments on research, the triggers and underlying mechanisms of marine geohazards remain poorly understood, and their occurrence, cause-effect relationships, and impact scenarios are largely speculative. The situation and needs are similar to those associated with onshore geohazards, as it is explained in challenge 3. Multi-hazard approach to risk reduction, of the Strategic Theme # 14. Understanding and forecasting marine geohazards, their causal links, their probability of occurrence and properly estimating their potential socio-economic impacts, remain outstanding challenges for the society. The common challenges we face include: (i) improving offshore observations to better characterize the sources of geo-hazards; (ii) enhancing numerical models of event generation, their inter-relationships and their role as tsunami sources; (iii) reinforcing monitoring networks and establishing early warning systems based on multi-hazard scenarios; and (iv) transferring the knowledge to the administration and stakeholders to develop adaptation strategies.

Gas, as in free gas or in clathrate form (gas hydrates), is present in sediments worldwide. Its origin can be as a product of seepage from deep hydrocarbons or produced by microbes through the degradation of organic matter. Gas bubbles are ubiquitous in the organic-rich muds of coastal and shallow sea waters, while hydrates predominate in continental slopes, due to the low temperatures or high pressures needed to satisfy their stability. In very cold regions like the Arctic, methane hydrates can occur on the shallow continental shelf. Methane, the predominant biogenic gas in marine sediments, is one of the most important greenhouse gases. An increased release from the ocean into the atmosphere could intensify the greenhouse effect. Investigations of methane hydrates stability in function of temperature fluctuations, as well as of methane behavior after it is released, are urgently needed. Another interest in gas stems from its potential as anthropogenic hazard in pipelines and production facilities and as a natural hazard inducing subsidence, slumps and slides. The increase in pore pressure, expansion of sediment volume, and development of free gas bubbles can all weaken the sediment. A better assessment of shallow seafloor gas presence is needed to assist with design, installation, management, and insurance of temporary and permanent seafloor engineering installations associated with telecommunications, energy and marine exploration interests, as well as engineering by port and harbor companies.

Erosion, scour and seafloor sediment mobility occur in both shallow- and deep-sea environments. These processes pose a threat to submarine infrastructures due to their potential for burial and undermining. Seafloor erosion and mobile substrates may be induced by oceanographic phenomena such as waves, tides and bottom currents, by gravity flows (e.g. turbidity currents), or by interaction of different processes (e.g. gravity flows and bottom currents). Local intensification of bottom currents can trigger erosive processes, undermining slopes and steep flanks. Downslope turbidity currents have strong potential for dragging and undermining due to their ability to transport large sediment volumes at high velocities over large distances. The limited direct monitoring of the related processes hinders the identification and understanding of such processes. Conventional geophysical techniques may underestimate their frequency and magnitude, because turbidity currents or bottom currents may not necessarily cause significant or sudden seafloor changes. The challenge for the future is to better understand and quantify seafloor change rates induced by erosion or sediment transport. This requires collaboration of geologists, geophysicists and physical oceanographers and deploying deep-sea monitoring and mobility sensors. Repeated high-resolution bathymetric surveys should be done to measure rates of seafloor change, which are in turn needed for numerical models of scour initiation and spatio-temporal evolution.

FIGURE 5.3–Aftermath of the 2004 Indian Ocean tsunami. Image by WikiImages from Pixabay.

Submarine landslides involve the rapid movement of the seafloor and the subsequent transport of sediment and/or rock across continental margins. They can generate tsunamis, damaging offshore infrastructures and coastal communities. The occurrence of submarine landslides is related to a complex equilibrium between driving (e.g., gravity and seismic loading) and resisting stresses. Submarine landslides of different sizes have been mapped on the continental margins of Spain and adjacent countries, indicating that such events constitute a hazard. Despite recent significant improvement in our knowledge of submarine landslide activity, there are still outstanding questions related to their onset, post-failure evolution and timing. Major challenges linked to these questions are numerous. We need to assess the mechanisms by which failure initiates, including the role of seismic shaking vs seismic strengthening, and to identify the mechanisms by which pore pressure develops in marine sediments. Marine sediments and, particularly, weak layers must be better characterized, and we should understand the mechanisms of submarine landslide propagation and their dynamics. Finally, events have to be dated to evaluate submarine landslide tsunami probabilities. Facing these challenges require using geological, geotechnical, geophysical and numerical modeling approaches. Extensive in situ testing to better characterize the geotechnical parameters is needed for modeling, whereas time-lapse and/or continuous monitoring of slope environments is required to picture landslide dynamics. There is also a need to compile catalogues with distributions of submarine landslides accounting for uncertainties in location, magnitude, release mechanisms, post-failure evolution and return periods to support the development of Probabilistic Tsunami Hazard Analysis (PTHA).

Submarine faults can produce earthquakes that generate seismic waves, ground shaking and huge tsunamis that devastate offshore and onshore infrastructures and cause massive loss of human lives along coastal areas. The largest submarine earthquakes, which occur along the megathrust zone of subduction zones, have caused some the most destructive natural disasters, such as the tsunamigenic earthquakes of 2004 in Sumatra-Andaman (Mw9.2) (Fig. 3) and of 2010 in Japan (Mw9.1). Many potentially seismogenic faults have been identified and their study initiated, but others have remained silent in the instrumental and historical periods and their seismic potential remains yet unrecognized. This includes fault systems surrounding the Iberian Peninsula, such as the source area of the Lisbon earthquake, which devastated the SW Iberian coasts in 1755, or the North African system. The major research challenges to assess the seismic and tsunamigenic potential of submarine faults include the identification of the largest active structures, the determination of fault geometry and properties, the estimation of slip rate and slip distribution, and the numerical simulation of the dynamic rupture. This should be combined with better estimates of recurrence periods, displacement per event, and elapsed time since the last event. Fulfilling these goals will require improved offshore geophysical, geological and seismological observations by densely covering larger areas during longer periods (Newman, 2011).

Better offshore data will allow identifying and mapping major faults and inferring fault-rock properties using geophysical methods, characterizing them with geological sampling, and monitoring their activity with ocean bottom seismic networks and seafloor geodesy. These data are required to improve dynamic rupture models and to better characterize the seismogenic and tsunamigenic potential of fault systems. The information on fault location, source properties and dynamics and of recurrence periods should be incorporated in source catalogues for PTHA and integrated in the development of tsunami forecast models for early warning systems. This chain of science-based knowledge must be integrated into actions leading to community resilience based on education, awareness, emergency planning and risk mitigation.

Although earthquakes are a natural phenomenon, they can also be triggered by human activity (the so-called induced seismicity). Offshore industry operations involving fluid extraction or injection, such as enhanced oil recovery, refilling of depleted reservoirs or CO2 sequestration, may induce moderate magnitude seismicity disrupting life in local communities, as evidenced by the CASTOR crisis offshore Castellon (Spain) in 2013. These activities, which are likely to increase in the years to come due to growing climatic pressure and energetic demand, require baseline studies of the local seismo-tectonic setting, continuous seismological monitoring to detect deviations from background seismicity levels, development of methods to distinguish natural and induced events, and the establishment of protocols to supervise operations based on the objective evaluation of the related hazards.

Volcanism occurring close to coastal areas is also a source of marine hazards. The offshore impact of near-coast volcanism and its associated processes may have catastrophic consequences with multi-scale implications. Submarine volcanic eruptions, which are the most frequent, can cause damage to communication and energy infrastructures, but hardly produce major impacts on population, infrastructures or the environment. Due to its major relevance, here we concentrate on volcanic islands. They are common in all the oceans, and are threatened by multiple geohazards (volcanic eruptions, earthquakes, large-scale landslides) that can be triggered and amplified by climate change (e.g., sea level rise, glacier melting). These natural phenomena, acting simultaneously or in a concatenated way, may lead to unpredictable cascading effects leading to large tsunamis. This was evidenced by the 2018 eruption of Krakatau (Indonesia), during which the volcanic activity led to a massive landslide that prompted a destructive tsunami. Consequently, predicting, preparing for, and recovering from the offshore effects of their volcanic activity and associated phenomena is a worldwide pressing cause of concern. One of the main research challenges is to correctly predict the outcomes of such multi-hazard scenarios and their impact on the surrounding ocean. Work towards this goal requires establishing a robust methodology to model realistic hazard scenarios to better forecast and quantify the offshore effects of eruptive activity of volcanic islands, as well as their interactions and impacts.

Tsunamis constitute a formidable hazard that can originate from a variety of sources such as earthquakes, landslides, volcanic eruptions or meteorite impacts. Although they are relatively infrequent, their extreme impacts can cause many victims and enormous economic losses. However, their study suffers from large uncertainties. In recent times, several major tsunamis, such as the 2004 Indian Ocean and the 2011 Tohoku ones, have occurred around the world, causing hundreds of thousands of deaths. The fact that similar sources behave differently makes that tsunamis many strike us unexpectedly. Tsunami hazard is not only unpredictable, in the sense that triggering mechanisms cannot be precisely forecast, but it also presents a large degree of uncertainty. Europe has also a long record of large destructive tsunamis, not only in historical times (e.g. Lisbon 1755 and Messina 1908) but also recently (e.g. Turkey and Greece in 2017). Increasing the capabilities for mitigating tsunami-related risks can have tremendous societal consequences. Measures are required to strengthen such capabilities, both towards providing services for scientists and operational systems, and to enhance the three first priorities of the SFDRR. Forthcoming challenges include near real-time tsunami source inversion, much Faster Than Real Time tsunami simulations and its use in Tsunami Early Warning Systems, the development and operational use of Probabilistic Tsunami Forecast for early warning and rapid post-event assessment, development of a standardized PTHA considering different sources, estimation of the economic losses associated with tsunamis at several spatio-temporal scales, the development of higher resolution models for tsunami risk and hazard assessment, and the development and provision of standards for tsunami interoperability between researchers, countries and operational systems. The building of a European tsunami research network also remains to be done.

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CHALLENGE 6

ABSTRACT

The Arctic and the Antarctic are the regions where temperature has raised most and faster than any other Earth's place, producing a large number of impacts and feedback to the polar/climate system. Moreover, since polar oceans play a fundamental role in the Earth's climate and global ecosystem, those changes produce climate consequences at mid latitudes . The study and monitoring of the poles from a global perspective and holistically is fundamental to better assess and understand the changes the polar regions are facing and its consequences on ocean circulation and climate, changes on the oceanic biogeochemistry composition and consequences on the oceanic living beings. Understanding the past to infer the future is another important leg to understand how the whole system is changing. The revision of the going on transformation and the continuous monitoring can be achieved with the combination of large amounts of observations (in situ and remote sensing) and numerical models.

KEYWORDS

arctic | antarctic | polar oceans | climate change | ice melting | monitoring | modelling | biogeochemistry | anthropogenic pollutants | biology | living beings | geological records

CHALLENGE 6

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1. INTRODUCTION AND GENERAL DESCRIPTION

Polar oceans play a fundamental role in the Earth's climate and global ecosystem. They absorb large amounts of heat and carbon from the atmosphere and seafloor emissions (in fact, the Southern Ocean represent 40% of the global uptake of atmospheric CO_2 by the ocean; Gruber et al. 2019); supply dissolved oxygen and nutrients to other oceans; interact with the surrounding marine and terrestrial ice, affecting the surface albedo, as well as with sediments on the seafloor, constraining the freshwater balance and sea level; host sites of deep water formation, which play a crucial role in the global ocean circulation and global climate; harbor an immense variety of marine life including micro-organisms, seabirds, whales and fish, and provide food and other economic and cultural services. In recent decades, polar regions are suffering rapid changes in response to climate change including changes in ocean circulation, ocean properties, sea-ice cover, sedimentary dynamics, and ecosystems, among others (Schofield et al. 2010, Comiso, 2012, Stroeve et al., 2012). There are a number of key findings identified by the Intergovernmental Panel on Climate Change (IPCC) in the polar oceans (e.g. acidification, loss of ice, anthropogenic impact, etc.) that are affecting their productivity, ecosystems and their functioning in general (Meredith et al. in press). These changes are having consequences that affect the rest of the planet and need to be fully understood to predict and reduce risks at both, regional and global scales. It is, therefore, a priority, and a scientific challenge, to understand the functioning of the polar oceans' ecosystems and related oceanographic and sedimentary environments, and their responses under different scenarios of global warming. The complexity of the functioning of the polar oceans and their ecosystems combined with the very sparse data coverage (as a result of their remoteness, inaccessibility, and logistical constraints) hampers the efforts to achieve these challenges. Therefore, we need multi- and interdisciplinary coordinated efforts supported by land and ship-based monitoring programmes, integrated oceanographic multiplatform approaches and remote sensing observations, to collect and interpret field data that help us to advance in the urgent understanding of the functioning of the polar systems.

The Polar Ocean's challenge aims to assess the current state of knowledge of the polar oceans from a chemical, physical, geological and biological perspective, to identify the main gaps of knowledge and propose actions that help the scientific community to predict, and when possible, mitigate the effects of global change in the polar oceans and the Earth's climate system. Specific challenges include the need of exploring the diversity and ecology of the food web from planktonic and benthic communities to top predators; polar ocean circulations and their interactions with the overlying atmosphere and ice; sources, pathways, occurrence and/or bioavailability of chemical (from bulk and essential elements to toxic anthropogenic pollutants); sedimentary process and seafloor gas hydrates emission; and the study of past ocean-ice sheet interactions to understand the ongoing and future changes under different warming scenarios.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

The increase in the liquid Arctic Ocean freshwater budget is reported in many papers (Meredith et al. 2019). The main causes of this increase are the glaciers and Greenland ice sheet melting, increase of river discharge, increase of Arctic precipitation and the melting of sea ice. The total liquid freshwater volume is projected to increase 50% between 2000 and 2100. Thus, the Arctic freshwater cycle will accelerate in the 21st century with significantly increasing inflow, outflow, and storage of freshwater. Therefore, it is possible that large freshwater discharges to the Atlantic could occur. This would induce changes on the Atlantic circulation as well as impact on the atmospheric currents, producing dramatic impact on the climate up to middle latitudes regions. Additionally, ice, in both poles, contents important amount of trace elements (natural and anthropogenic) and nutrients that, when melting, are released to subjacent water mass, affecting its chemical composition and stoichiometry, biogeochemical cycles and consequently to the whole ecosystem. If we can better monitor the changes and improve the models, we could better understand and predict the expected changes, and therefore start to prepare for the severe changes that Spain and Europe will face. Moreover, better projections of glaciers and ice sheets melting and its impact on sea level rise, should permit to implement adaptation responses to coastal impacts and risks.

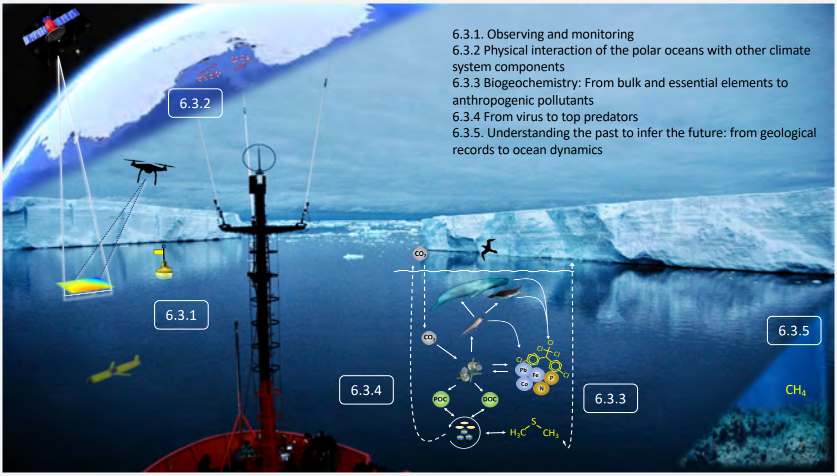
Addressing the challenges described is this chapter is of paramount importance to propose actions in the Polar regions that help to mitigate the net global warming, as the ocean Fe fertilizations. Iron limits primary productivity in High Nutrients Low Chlorophyll regions (HNLC), such as some areas of the Southern Ocean. Artificial Fe fertilization in HNLC regions induce blooms of phytoplankton, sequestering carbon from the atmosphere and producing organic particles that sink to the deep ocean. However, its viability and side effects on the ecosystem remain unclear, mainly by the lack of knowledge of the functioning of the ocean system.

3. KEY CHALLENGING POINTS

3.1. Observing and monitoring

Observational data and model simulations are the foundations of our understanding of the climate system. Undoubtedly, satellite data dominates in operational mapping tasks and data ingestion by assimilation systems. Other in-situ observations complete the Polar observational systems such as land and ship-based monitoring programs, Lagrangian drifters, AUV (Autonomous Underwater Vehicle), gliders, RPAS (Remotely Piloted Aircraft System), or moored, among others multiplatform integrated systems. However, there remain fundamental gaps in Polar research that pose a challenge for the routine integration and assimilation of existing and potential new space-based, drone and in-situ products into forecasting models. To reduce knowledge gaps and address challenges, the community needs stable, novel and dense satellite-based, RPAS and in-situ observation, and to advance on computing methods. In situ observations in polar regions are very scarce, and this is an important gap to understand the ongoing change and their global influence. A more extensive in situ dataset would permit to study phenomena at smaller spatial

FIGURE 6.1–Schematic representation of the proposed key challenges



and temporal scales than the satellites to better understand some of the on-going changes. Moreover, the in-situ data provide a more robust quality assessment of the satellite products. Satellite data often contain uncertainties caused by biases in sensors and retrieval algorithms, as well as inconsistencies between continuing satellite missions with the same sensors, which can be reduced with a large and precise net of in-situ data.

Therefore, the RPAS, gliders, Polar Argo, sail-drones, and drifter observations should be promoted in the region to better understand the physical oceanography of the region. Moreover, larger number of bio- geo- and chemical in situ observations are required to better understand the interdisciplinary links. Observations of chlorophyll, suspended matter, pH, pCO_2, dissolved oxygen, inorganic nutrients, trace elements, among others, are fundamental to properly achieve the challenges described below. These parameters can be measured from ship-based instruments, but also with autonomous sensors recently developed.

Additionally, it is necessary to establish the operational guidelines to operate RPAS in polar regions to monitor the wild fauna without disturbing animals in their natural environment. A fleet of underwater gliders would contribute to fill this gap, providing quasi real time data to monitor the upper ocean physical, biogeochemical and biological variability.

To increase the technological and logistic capabilities of the current Spanish polar fleet is essential to guarantee an increase of polar ocean in situ observations. Increasing the international exchange opportunities on access to research polar capabilities is also a priority. Moreover, a Polar data base should be built to store and freely distribute the data acquired by Spanish funded projects. This should be organized and coordinated with the "Comité Polar Español" (since they are working on this). This data set, also called Polar Observatory, should contain data from both poles, Arctic and Antarctic, and both in-situ observations but also remote sensed observations processed by Spanish teams.

The other main pillar for polar monitoring is the observations from satellites. Some of them were specifically designed for studying the Polar regions, i.e. CryoSat2, IceSat2, and some Sentinel missions, but many others are also used for Polar observations. The quality and quantity of remote sensing data has exploded since the dawn of the space era, enabling comprehensive monitoring of Arctic and Antarctic changes. However, resolution and accuracy of the current observations should be enhanced to improve our knowledge on the changes ongoing on the poles. Hence, CSIC researchers could participate in the definition of requirements of new satellite missions and in the development of its data processing operations (as already occurred for two ESA missions, SMOS and FLEX or NASA SWOT mission or leading the G-TERN ESA Earth Explorer 9 proposal for a Polar Science mission). On the other hand, by enhancing the data processing of the current satellite missions, it is possible to improve the quality of the observations as well as to improve the resolution by combining observations from different satellites (synergies).

Sea ice thickness and extension, as well as glacier melting rate are some of the main parameters to monitor the polar changes. Several satellites are measuring sea ice thickness, but by performing synergies among them, new maps with higher temporal resolution covering the whole ice thickness range could be produced. Assessing the ice sheets and glaciers melting rate with good accuracy is fundamental to predict the sea level rise and therefore to act on adaptation on our coastal regions (IPCC AR5 Special rep. 2019). The combined observations from NASA, ESA and national satellites could improve those estimations. Furthermore, the development of new processing techniques (using synergies) to quantify the effect of climate change to biological parameters (as for example, secondary producers as important in the polar food chain as krill) and on hydrological parameters (as for example, increased land and river runoff) are clear recommendations.

Therefore, improving the resolution and accuracy of many satellite observations, as well as acquiring new parameters by combining existing data, are essential to study several ongoing Arctic and Antarctic processes. Part of these gaps could be assessed by strengthening the remote sensing data processing, by creating stronger satellite data processing centers with high computation capacity to develop new algorithms, new processing tools and using multisensor image fusion techniques, among other techniques. Research towards new measurement techniques, spaceborne mission concepts and new opportunistic spaceborne data could also contribute to this challenge

3.2. Physical interaction of the polar oceans with other climate system components

Polar oceans are to a large extent covered or surrounded by ice, both marine and terrestrial, which is coupled to the oceanic and atmospheric circulation, and represents one of the most sensitive components of the climate system to anthropogenic forcing. In the Arctic, the current rate of atmospheric warming is substantially higher than in lower latitudes of the Northern Hemisphere. This phenomenon, called Arctic Amplification, is mediated by sea ice loss, and has been linked to changes in mid-latitude weather, including recent increases in the occurrence of cold spells. However, observational and modelling support has proven it difficult. Possible explanations are that the sea-ice loss signal in mid-latitudes is small, indistinguishable from the large natural variability in the short observational data record, masked by other forcing and/or underrepresented by the lack of model realism (e.g. ocean feedbacks; England et al. 2020). In spite of this, future projections consistently show an overall reduction of cold extremes in response to additional losses of Arctic sea ice (e.g. Ayarzagüena and Screen 2016). In the Southern Hemisphere, Green House Gases (GHG) forcing and stratospheric ozone depletion as a result of the emission of ozone depleting substances have driven many of the observed changes in the last decades. In particular, ozone depletion has largely contributed to poleward shifts and stronger westerlies at high latitudes, thereby favoring warming of sea surface temperatures around Antarctica and sea ice loss. Unexpectedly, an expansion of Antarctic sea-ice extent (Comiso et al. 2017) has been observed during the satellite era, which raises questions on current understanding of the atmosphere-ocean-ice interactions. The level of stratospheric ozone recovery following the Montreal Protocol bans, and its competing effects with those expected from GHG increases represent major sources of uncertainty for the future evolution of Antarctica.

Regarding polar regions, a question of major concern is sea-level rise from terrestrial ice loss. Ocean-ice-sheet interactions have played a major role in the recent acceleration of ice-mass loss from both the Greenland ice sheet (GrIS) and the Antarctic ice sheet (AIS), which has resulted in an accelerated sea-level increase over the last decades. In the GrIS, the ice loss is roughly equally distributed between increased surface melting and increased discharge from marine-terminating glaciers (Straneo and Heimbach 2013). In the AIS, ice-ocean interactions play an even more important role. Large sectors of the East AIS (EAIS) and most of the West Antarctic Ice Sheet (WAIS) are grounded below sea level. As a result, Antarctica is surrounded by ice shelves and its ice is strongly exposed to the ocean. Recent observations have shown that the AIS is losing mass along its periphery, mainly within the WAIS, due to accelerated glacier flow and discharge caused by enhanced sub-shelf melting.

The need for enhancing synergies between observations and models is a common challenge to both polar regions. Observations, including proxies, allow testing and improving models, which in turn are crucial to gain understanding of the complex ocean-ice-atmosphere interactions, particularly for many polar areas that are barely accessible. Although much progress has been made in the last decades, questions remain regarding the sea, atmosphere and ice dynamics and their interactions. Better understanding of processes and their implementation in state-of-the-art models would shed light on polar responses to climate change, and their remote influences.

Regarding future sea-level projections, the WAIS is the main source of uncertainty (Pattyn et al 2018). This uncertainty is closely linked to our lack of understanding of ice-ocean interactions in marine ice sheets, stemming both from observational and modelling shortcomings. Technical challenges associated with direct access to sub-ice shelf cavities have hampered a better understanding of such processes, leading to an inability to properly represent these processes in ice-sheet, ocean, and Earth System climate models (Copernicus Marine Service evolution strategy, 2018). A full understanding of ice-ocean interactions is crucial to better constrain the response of the ice sheets to climate change. There is widespread community consensus that progress in this line requires concurrent and long-term records of glaciological, oceanic, and atmospheric fields at the ice sheet-ocean margins where heat, freshwater and nutrient exchanges take place. From a modelling point of view, technical difficulties associated with the different resolutions and timescales of ocean and ice, the small spatial scales involved, and the high computational costs are also considerable. Currently there is an important effort from the community to better understand effects of ice–ocean interaction in coupled models, and interactively coupled ice–ocean models resolving both the ice flow and the circulation of water below ice shelves are starting to become available (Dinniman et al. 2016 and references therein). However, such simulations are currently limited to ocean-ice only components, regional spatial domains and short time-scale simulations. Continental-scale ice-sheet modelling, in turn, generally makes use of simplified parameterizations which do not always perform satisfactorily compared to coupled ice-ocean models. While improved observations should allow building better parameterizations, the challenge is to include these within fully coupled Earth System models to obtain projections with significantly reduced uncertainties. This will undoubtedly also require an important increase in computational facilities and efficiency. In the light of the large spread of model results, international initiatives designing coordinated experiments are also warranted.

Challenges in the modelling of polar ocean circulation, include issues already discussed, about sea-atmosphere and sea-ice interactions that impact the freshwater content. Despite these challenges, long time series of large scale Arctic ocean reanalyzes products have started to be available since recent times in the Copernicus Marine Environment Monitoring Service (CMEMS). The state of art for these large scale models still requires augmenting the resolution above their current one of about 12–16 km. These resolutions are eddy permitting from the Equator to the Nordic Seas, but are still far from being eddy resolving in the Arctic. Other limitations and biases in the accuracy of these models, which regard sea-ice thickness, the signature of Atlantic waters, etc., will also benefit from an increment of the resolution, which in turn require an increment of the computational resources.

3.3. Biogeochemistry: From bulk and essential elements to anthropogenic pollutants

Understanding how climate change alters polar ocean biogeochemistry is a priority for the oceanographic community. Any change that affects the occurrence, sources, pathways and/or biological and photochemical availability and transformation of chemical elements will affect directly to the functioning of the ecosystems at the regional and global scale. Whilst there are multiple chemical elements and compounds that play a critical role regulating biochemical function in polar marine organisms (e.g. C, Fe, Co, etc.) there are others that negatively affect ecosystem health (e.g. Persistent Organic Pollutants – POPs, Hg, etc.).

- Carbon Cycle Components: The CO_2 uptake by the Southern Ocean plays a determinate role in the variation of the global ocean carbon sink. It represents 40% of the global uptake of atmospheric CO_2 by the ocean which, contrast with the Arctic Sea and Nordic Sea that represent only a 3% of global ocean carbon sink (Khatiwala et al. 2013; Gruber at al. 2019), so understanding this carbon sink and its relationship with environmental and climatic changes is very relevant in terms of climate projections. Due to their low temperatures, polar waters, in addition to promoting the dissolution of CO_2, weaken the dissociation of bicarbonate ion (majority ion of the carbonate system in seawater), and also facilitate the dissolution of calcium carbonate ($CaCO_3$), structural compound of many biological organisms. Therefore, already in natural or pre-industrial conditions, polar regions calcareous marine organisms have adapted to conditions with low $CaCO_3$ saturations. The progressive anthropogenic increase of CO_2, is causing polar regions to rapidly increase the $CaCO_3$ unsaturation of epipelagic waters, hindering the development of species with calcareous structures. Moreover, the decrease in salinity due to global warming in polar areas leads to a decrease in the pH buffering capacity, which amplifies the effect of the impact of anthropogenic CO_2 uptake (Zhang et al. 2020). The CO_2 system is not the only carbon compartment impacted by climate change in Polar Regions. Increased Arctic rivers discharge, sea-ice melting and weakening of the thermohaline circulation have been suggested to alter the organic matter cycling and, particularly, the major pool of dissolved organic carbon (DOC). Global warming is already producing extensive thawing of frozen soils and permafrost, increasing the export of DOC to the Arctic Ocean. Global warming is causing decreases in the summer minimum sea-ice extent in both poles. Sea-ice melting releases the DOC produced by phytoplankton within the ice, changing the concentration and quality of DOC in the surrounding waters. Global warming is also affecting the Gulf Stream and associated Atlantic Meridional Overturning Circulation (AMOC), which has apparently weakened and will continue to weaken during the 21st century. Future projections of the Southern Ocean circulation also predict a weakening of the formation rates of Antarctic Intermediate and Bottom waters. These changes in ocean circulation and water mass formation dramatically affect DOC transport and injection in the deep ocean. Therefore, it seems that global warming will strongly affect the physical processes that control the concentration and quality of DOC, but these impacts are largely unknown as well as their overall effect in the carbon cycle of polar regions.

- Trace metals: The external sources of trace metals to the Polar oceans are different for each pole and not well constrained. Atmospheric deposition (dry and wet), advection of water masses, hydrothermal vents or ice melting are identified as important sources of trace metals (Chever et al. 2010; Tovar-Sánchez et al. 2010). On the other hand, melting of the polar ice cap and disintegration of ice shelves are leading to the input of continental trace metals mainly related to glacial erosion and the exposure of bedrock. Recent works have demonstrated that biological recycling is considered an important mechanism in the Antarctic for concentrating and retaining metals in the surface layer waters (Tovar-Sánchez et al., 2009). As many of the elements underpinning biogeochemical process (e.g. Cd, Cu, Fe, Mn, and Zn) have a short or intermediate residence time in oxygenated waters, any mechanism that can increase or decrease the concentrations and persistence of trace elements in surface waters could enhance or weaken overall marine primary productivity in polar regions, these effects are particularly important under the pressure of ongoing climate change.
- Trace gases and aerosols: Climate warming-driven changes in the temperature, salinity and stratification of the polar oceans are paralleled by changes in sea ice extent, thickness and melting rate. These have consequences for the exchange of energy and mass between the ocean and the atmosphere, which affects the heat and pressure distributions and therefore the respective circulations. The aforementioned changes in ocean and ice also have consequences for polar ecosystems as emitters of climate-active substances such as water vapor, trace gases and aerosols. Increased evaporation enhances cloudiness, precipitation and heat retention. Variations in the emission of sulfur, nitrogen and halogen volatile compounds from the marine microbiota and the snowpack may have profound impacts on the oxidative capacity of the polar atmosphere and on the formation, albedo and lifetime of clouds. *Therefore, understanding the biogeochemical processes occurring near and across the ocean/sea ice-atmosphere interface, and their feedbacks on climate, is of high priority*. Specifically, these are the knowledge gaps that need to be addressed: improve our understanding of the feedbacks of polar pelagic, sympagic and continental cryospheric ecosystems on climate; decipher and map the distribution of the emission of climate-active substances in the two poles; quantify and characterize aerosol sources in the polar

atmospheres: precursors, conditions, processes and timing; quantify the role of wave-sea ice interactions in sea spray production; address the influence of sea ice melt, river freshwater and glacier ice/subglacial discharges on the production and emission of climate-active substances; assess the relative importance of continental (human activities, vegetation, animal colonies, snowpack) and marine (plankton, sea-ice microbiota, sea spray, snow on ice) sources of climate-active substances.

- Organic Pollutants: Long-range atmospheric and oceanic transport of organic pollutants, including persistent organic pollutants (POPs), as well as the perturbation of their biogeochemical cycling under environmental global change, and bioaccumulation of contaminants in polar food chains represent major challenges for both ecosystems and human health. Humanity currently uses 300,000 synthetic chemicals with potential to reach the environment, in addition to hydrocarbons emitted due to massive use of fossil fuels. The more persistent fraction of this anthropogenic perturbation of the chemical composition of the biosphere can reach remote ecosystems, including the Arctic and Antarctica. In addition, the increase on human activities (research stations, tourism, maritime operations and transport) in Polar areas is likely to lead to an increase in potential local sources of not only POPs, but also other anthropogenic chemicals. The continuous release of hundreds of thousands of emerging contaminants are recognized as the major threats to the dynamics and structures of polar ecosystems, due to increased bioaccumulation potential and persistence at low temperatures. Thus, due to their low resilience, the study of the functioning of ecological communities is pressing and of strategic importance. On the other hand, snow deposition is a key mechanism for amplification of concentrations of volatile and semi-volatile organic pollutants in polar regions, with influences from glaciers to water column dynamics, and implications on the bioaccumulation in food webs and their effects still unknown. A multidisciplinary approach is fundamental to assess the link between all environmental factors potentially affecting pollution in polar ecosystems, and how the impact of these will vary under current environmental and climatic change.

Therefore, the multidisciplinary study of the biogeochemical cycles of bulk, essential and toxic elements and the influence of anthropogenic compounds under different scenarios of climate change is a priority in Polar chemical oceanography. To address this challenge, the establishment of long-term (decades) *interdisciplinary monitoring programs including coastal observation platforms and oceanographic campaigns is needed.*

3.4. From virus to top predators

Polar ocean ecosystems are subjected to harsh environmental conditions such as low temperatures and darkness in winter, extreme seasonal shifts in solar radiation, high UV exposure in summer and seasonal changes in the sea ice cover. In spite of this apparent inhospitality, polar ecosystems host diverse active planktonic communities that drive biogeochemical cycles and support higher trophic levels.

Since polar regions are more strongly impacted by global change than temperate regions, there is an urgency to determine how polar organisms will be affected by inevitable changes in the ecosystem and how those changes will affect life in other regions of the planet. Gaining strong understanding on the diversity, endemicity and ecology of polar life is key to tackle these problems.

- Plankton: Virus, prokaryotes (archaea and bacteria), small grazers (heterotrophic nanoflagellates and ciliates) and phytoplankton are components of the microbial food web that is linked to the high levels of the food web by zooplankton. Microorganisms with key roles in the ocean carbon cycle may respond differently to global change, and this is more conspicuous in the polar systems where small changes in temperature can produce high responses. We should have in mind that global change, more than affecting particularly each of those groups, will affect the relationships among them. For instance, the increase of microbial activity will also enhance viral activity favoring the increase of released dissolved organic matter (DOM) from their hosts, as well as changes in the structure of the viral and host communities. In addition, warming may drive a shift of phytoplankton communities, favoring smaller phytoplanktonic cell sizes and disadvantaging of their main predators (zooplankton). As a whole, it seems that global change may contribute to an heterotrophication of the oceans and also of polar systems since heterotrophic bacteria appear to be more resilient to changing conditions.

Our present knowledge hints towards major changes in carbon fluxes and trophic interactions among planktonic organisms in the polar ocean. This stresses the need for increased spatial and seasonal coverage, including winter sampling focusing also in the top-down and bottom-up controls of processes involved. Also, long term monitoring is needed to provide reliable predictions on how polar aquatic systems will interact with climate change in order to better assess the resilience and adaptation of the ecosystems.

It is, therefore, a challenge to increase the coverage of our knowledge on planktonic communities along the year to better predict how the divergent future responses of planktonic organisms to complex multiple interactions will be expressed in the fragile polar ecosystems.

- Benthos: The Antarctic benthic ecosystem (like those of the deep sea) compared to other marine benthic ecosystems shows remarkably constant physical conditions; however, it is exposed to more physical variability and disturbance than had previously been thought. These conditions of isolation have been developed over the last 40 million years, during which marine life has adapted to a new habitat, and their distribution areas have been reduced. Endemism rates are as high as 97 % in some marine groups. However, despite the improved sampling and the new approaches of molecular phylogeny and phylogeography, the origin of the current fauna of the Southern Ocean remains a controversial issue. It is also essential to study the effects of climate change on benthic communities, particularly on the Antarctic continental shelf where one can find still relatively undisturbed environments (Ambroso et al 2017). The low to null supply of terrigenous sediments, the relative constancy of its physical conditions and the relative absence of human-derived impacts such as industrial fishing, make the Antarctic continental shelf a highly favorable environment for the development of high-density benthic megafauna communities. This makes Antarctic benthic communities look, more than one might think, like the communities with the highest known biodiversity in the world.

The study of pristine places is very important for learning about the state of the oceans before the impact of human beings. Because of the extreme environmental conditions of the Antarctic continental shelf – its distance from other continents, depth, and the weight of the continental ice – it offers us a great opportunity to better understand how a pristine ecosystem would normally be. Many aspects related to the physiological adaptations to extreme environmental conditions of benthic fauna, their longevity and survival, the mechanisms of reproduction in highly seasonal and apparently limited trophic environment remain some of the most exciting challenges for Antarctic benthic research.

The lack of observations is the main bottleneck for developing this research that could be addressed with the routinely use of ROVs with high-resolution cameras, the possibility of carrying out on-site and on-board experiments and the development of projects with international collaboration in which experiences and sophisticated equipment are shared.

- Top predators: In a food web, the organisms occupying the highest trophic levels are the so-called top predators. Their positions render these organisms as key species to detect changes from the bottom to the top of the trophic web as they reflect very rapidly the environmental changes occurring in the ecosystem (Hazen et al. 2019). In the marine environment this is particularly important due to the rapid changes detected. Polar oceans are among the planet region with the higher rates of change mainly due to the effect of climate change. Such changes are deeply affecting the entire food web and, in this context, top marine polar predators such as polar bears, seals and seabirds play a crucial role as sentinels of the ocean polar ecosystem. Sentinel species are characterized by exhibiting clearly identifiable responses to environmental change, affecting functionally the structure of the food web, responding to human impacts, showing great abundance and a wide geographic distribution, and a great ease of sampling (Hazen et al. 2019). Information about changes at population level, the factors driving such changes and the mechanisms behind are crucial to understand how the polar marine ecosystem is responding to the global environmental challenges. These factors include climate change, contamination, overfishing, habitat loss, invasive species, and emergent diseases. Examples of this can be found in Antarctic penguins where changes in population abundance have been related to cascade effects affecting their physiology produced by decline of krill stocks (Xavier et al. 2013). Our current knowledge about polar top predators is fragmented and scarce even in the case of the best studied species such as penguins, polar bears or some arctic seabird species. In general, information is limited to few species, few populations, restricted geographical areas, short periods of time and few biological traits. The recent technological advances in different aspects, such as bio-logging, remote sensing, omics techniques and modeling, among others, give us an opportunity to improve our knowledge on this important component of the polar ecosystem and therefore to get crucial information for its understanding.

To achieve this challenge, it is needed implement long-term interdisciplinary studies on very well identified key top predator species in several key places representing the areas where higher environmental rate of change can be observed and predicted.

A current picture of the research of the biotic, but also the abiotic, component of polar oceans is that each scientific community is focused on a specific trophic level or research area, working independently of each other, so that a deep lack of integrative studies can be identified. Therefore, a step forward is the integration of all the information at the different levels of the food web, studying the interaction among the maximum number of its components. This multidisciplinary/integrated approach will allow the analysis of the effects of current environmental changes and of the responses of the ecosystems, and will provide predictions for different future environmental scenarios.

3.5. Understanding the past to infer the future: from geological records to ocean dynamics

- Recent sedimentary processes: The Arctic and Antarctic regions are crucial components of the climate and oceanographic systems. The stratigraphic architecture and sedimentary record of their continental margins represent unique archives for understanding past climate and oceanographic configurations that can help inform future changes. However, glaciated margins remain poorly known because of sparse and usually low-resolution data. Past and sub-recent glacial and glaciomarine processes need to be reconstructed to define a glacial-interglacial sequence stratigraphy model, with emphasis on glacial terminations. These data are needed to provide information about forcing mechanisms of past climatic and oceanic changes and their rates of variability. These insights will enable better understanding of how ongoing environmental change impacts on sedimentary processes and habitats. In addition, it will provide needed constraints for the modelling of future scenarios.

For all this, geological and geophysical data is needed from glaciated continental margins where glaciers are grounded on land that is below sea level (marine-based). In addition, the recently observed intensive ice shelf sedimentation as a consequence of fast ice-shelves disintegrations is stimulating the study of the recent sediment record in regions where ice shelves were still existing at the beginning of the present century. These insights will be essential to understand the consequences of the past climatic and oceanographic variations in the discharge from the large ice sheets, stability of marine-ending glaciers, collapse/ fast retreat of ice-stream and sea-level rise. This understating will be also a necessary requirement to detect the human impact, and fundamental to set up future climate scenarios. Moreover, there is an increasing recognition that glaciomarine processes impact the biotic systems, both planktonic and benthonic. In the context of the rapid regional anthropogenic warming, the study of sediments under ice-shelves is indispensable to assess this impact.

Past and sub-recent glacial and glaciomarine processes need to be reconstructed in order to develop sedimentary models that provide information about past climatic/oceanic changes. This in turn will provide valuable information for addressing climate change adaptation.

- Gas hydrates and seeping of light hydrocarbons to the ocean: Thawing of underwater permafrost and the dissociation / dissolution of methane hydrates, an ice-crystalline mineral in which hydrocarbon gases are held within rigid cases of water molecules, can release significant amounts of methane into polar oceans and eventually to the atmosphere. These methane emissions often support unique chemosynthetic biological communities. In the Arctic Ocean, methane release occurs in the continental shelves and upper continental slope, mainly due to warming and inundation since Late Pleistocene time. Methane emissions to the seafloor have also been reported around the continental margins of the Antarctic continent where gas hydrates are also present. Nevertheless, it is commonly stated that the oceans are a 'minor source' of atmospheric methane, although this belief seems to be based on very thin evidence. Recent anthropogenic climate warming has raised concerns that large quantities of methane could be liberated representing a slow tipping point for Earth's contemporary period of climate change, even if only a fraction of that methane were to reach the atmosphere. Further to that, dissociation of gas hydrates may have an impact on pore pressure build-up in marine sediments and influence slope instability. *It is therefore needed to better understand and define the location, intensity, nature and changes in fluid flow emissions to the seafloor of the Polar oceans including methane/ethane emissions*. The climate of these areas is most rapidly changing with profound coincident changes in the adjacent ocean. The role of faulting, isostatic rebound, sediment burial history and past and present climatic variations in stability of gas hydrates and the gas trapped beneath them requires further assessment.

- Past ocean-ice sheet interactions and marine ice sheet instability: Knowledge of how polar ice sheets responded in the geologic past to warming climates will provide powerful insight into its poorly understood role in future global sea level change. Study of past natural climate changes allows us to determine the sensitivity of the ice sheets to higher-than-present atmospheric carbon dioxide (CO2) concentrations and global temperatures, thereby providing the opportunity to improve the skill and performance of ice sheet models used for Intergovernmental Panel on Climate Change (IPCC) future projections.

Paleoenvironmental records obtained around Antarctica and the Arctic continental margins are still limited in their geographical coverage and do not provide a basis for comprehensive understanding of how different sectors of Antarctica and the Arctic respond to climate perturbations. Geological data spanning ice-proximal to ice-distal environments across polar continental margins are needed to fully understand temporal and spatial ice volume changes that result from complex ice sheet-ocean-atmosphere interactions. These records should ideally target locations that have been identified by models and recent observations to be vulnerable to change (e.g., areas with marine-based ice sheets and intrusion of warmer deep waters on the shelf, which play a critical role in the current ice sheet mass imbalance). In addition, there should be an emphasis on obtaining, when possible, high resolution sedimentary records (i.e., orbital to annual) of cryosphere-ocean interactions leading up to and during past deglaciation episodes. These records (when compared with atmospheric records from ice cores) are key to: 1) understand how past changes in atmospheric circulation influenced the transport of ocean heat to the ice sheet grounding lines; and 2) define the nonlinear or variable ice margin retreat during climate warming, rather than having to assume a simple switch in the ice sheet models between advanced and retreated states. In addition to geological records, a prerequisite for understanding and modeling ice sheet and oceanographic processes in vulnerable areas of the polar margins is an accurate knowledge of the bathymetry beneath the ice shelves and tongues. *High-resolution bathymetric grids, now very sparse, will provide knowledge about features that can affect ocean circulation and therefore ice stream flow stability*. For example, the presence of deep troughs near the grounding lines can provide access for seawater with melting potential. *The combination of geological and bathymetric data will allow evaluation of the rates and magnitudes of sea level rise in future warming scenarios, which is a policy-relevant open question.*

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CHALLENGE 7

ABSTRACT

Coastal regions are historically the most inhabited and impacted by human activities. Global processes like climate change (i.e. warming, sea level rise, increased storm frequency, acidification, establishment of invasive species, etc.) now act together with local and regional anthropogenic pressures (habitat deterioration, eutrophication, pollution, etc.) affecting marine coastal ecosystems. Here we single out five of Spain's most iconic coastal ecosystems, to showcase the most important stressors and drivers and act as representative ecosystems for other coastal regions. We identify the science needed to resolve the main impacts, with a final objective to provide tools to achieve their preservation and restoration.

KEYWORDS

climate change | local pressures | vulnerability | sustainability | resilience | adaptation

CHALLENGE 7

A SUSTAINABLE COAST IN AN OCEAN OF CHANGE

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1. INTRODUCTION AND GENERAL DESCRIPTION

The coasts are land-sea interfaces attracting human populations since ancient times, thus shaping our economy, society, history and culture. Presently, half of the world population lives within 100 km of the coast and marine resources are essential for about 37% of humanity, meaning that pressures and impacts in coastal areas are a disproportionately large share of the human impact on the Biosphere. This long and intense relationship between humans and the sea through the coast has benefitted the former degrading the latter (Constanza et al., 2014). As an example, it is estimated that three quarters of the coastal ecosystems in Europe are presently in a bad condition and are unable to offer the services that they have historically provided to the human kind (European Commission, 2017).

Occupation and fragmentation of coastal habitats by urbanization and the transfer of pressures from land-based activities towards the sea and interface ecosystems are the main local drivers of this degradation. Urbanization is particularly severe in southern Europe in concomitance with tourism (e.g. about 90% of non-residents' pernoctances are spent in coastal areas in Spain). Modification of the surface and groundwater regimes by urbanization and agriculture as well as the introduction of noxious substances (organic matter, fertilizers, plastics, antibiotics, pesticides,...) are the main pressures transferred from land to sea. Other novel (e.g. energy production),

TABLE 1.1—Summary of drivers and pressures acting on the five iconic coastal ecosystems.

DRIVERS	PRESSURES	GE *	GR*	ED*	MM*	BI*
1. COASTAL USES	1.1 Urbanism	X	X	X	XX	XX
	1.2 Tourism	X	X	X	XX	XXX
	1.3 Port infrastructures	XXX	XX	X	XX	XX
	1.4 Maritime transport	XXX	XX	X		XX
	1.5 Pollution	X	XX	XX	XX	X
	1.6 Wildfires		XX			
	1.7 Habitat deterioration	XXX	XX	XXX	XXX	XXX
2. ENERGY / RESOURCES	2.1 Oil exploitation			X		
	2.2 SS Fisheries	XX	XX	XX	XX	X
	2.3 Aquaculture	XXX	XX	XXX		
	2.4 Agriculture	XXX	X	XXX	XXX	XX
3. GLOBAL CHANGE	3.1 Sea Level Rise	XXX	XX	XXX	XXX	XX
	3.2 River flooding and erosion	XXX	X	XXX	XXX	
	3.3 Wind regime		XXX	XX	XX	
	3.4 Extreme storms	XX	XX	XXX	XXX	X
	3.5 Warming	X	XX	X	XX	XXX
	3.6 Heat waves	X	X	XX	XXX	XXX
	3.7 Acidification	XXX	XX	X	X	X
	3.8 Deoxygenation	XXX	X	X	X	
	3.9 Eutrophication	XXX	X	X	XXX	X
	3.10 HABs /jellyfish	X	XXX	XX	XX	X
	3.11 Allien spp	X	X	XXX	XXX	XXX
	3.12 Pathogens		X	XX		XXX
4. GOVERNANCE	4.1 Jurisdiction fragmented	XXX	XXX	XX	XX	XX
	4.2 Science transfer to society	XXX	XXX	X	XX	XX
	4.3 Weak co-creation	XXX	XX	XX	XX	XXXX
	4.4. Weak compliance	XX	XX	XX	XXX	

*GE: Guadalquivir Estuary; GR: Galician Rias; ED: Ebro Delta; MM: Mar Menor lagoon; BI: Balearic Islands. The number of Xs marks the relative intensity of the pressure on basis of the expert judgement of the authors and collaborators of this chapter.

growing (e.g. finfish aquaculture) or long-established (e.g. fishing and maritime infrastructures such as harbours or navigation channels) uses add to the ever-increasing pressures on the coast. They create wide and synergic impacts on coastal ecosystems including eutrophication, hypoxia, water-quality losses, biodiversity destruction, harmful algal blooms, jellyfish outbursts or coastal erosion among others. Global processes like sea level rise, storm surges, changes in wave regime, river flooding, ocean acidification or the introduction of alien species add to these stresses, affecting vulnerable coastal areas. Sea level rise will bring permanent submergence, erosion, flooding and salinization affecting countries like Spain, which concentrates a large portion of its economy, infrastructures and services in the coastal zone.

Evidence of coastal degradation to alarming limits are unquestionable across Spain and affect ecosystems like the Mar Menor or the Guadalquivir estuary, which are not only sources of economic and natural capital but also icons of our cultural identity as a country. We present five iconic ecosystems as paradigmatic sites to provide a diagnosis of coastal systems in Spain and to offer a glimpse of the challenges to science to preserve them. These iconic ecosystems are those mentioned above plus the Galician rias, the Ebro Delta and the coast of the Balearic Islands. They suffer partially overlapping but not identical pressures that vary in strength across areas (see Table 1). Each of them can be seen as a claim from society to the scientific community to provide the knowledge and tools for their preservation and restoration. It is a challenging demand since the five convolve heuristic difficulties inherent to the nature of coastal dynamics (nesting of different scales, coupling of physics with chemical and biological processes, high-frequency interactions, land and sea interactions..) with the prism of intense and frequently conflicting demands they receive (agriculture, fisheries, aquaculture, navigation, tourism, conservation…). The complexities and uncertainties involved in this deconvolution hamper the establishment of neater cause and effect connections and, therefore, the undertaking of firm management actions to prevent the degradation of its natural value.

2. IMPACT IN BASIC SCIENCE AND POTENTIAL APPLICATIONS

In each of the five iconic ecosystems, this challenge identifies the science needed to resolve the main impact of the pressures. The final objective is using this understanding to provide tools to achieve their preservation and restoration. Therefore, achieving this objective will bring knowledge which application is straightforward.

It is an ambitious objective since it involves a double viewpoint: (i) a reductionist analysis of concrete pressures and processes; and (ii) a holistic perspective to obtain the necessary integration in ecosystems where everything is connected to everything. Focusing this double perspective is particularly challenging in the coastal zone owing to its transitional land-sea nature where both human and natural processes accrue. The advances necessary in basic science include developing the capacity to: (i) nest different scales (meso, submeso, tidal, turbulence…), processes (physical, chemical, biological…) and disciplines (natural, societal, computing, technology…); and (ii) understand short and long-term changes, and the specific role of climate change. These two capacity needs are strongly linked to chapters 1 (ocean observation) and 2 (ocean variability and climate). These advances will provide answers to key and embracing questions which are relevant not only for the five iconic ecosystems but for the research community involved in coastal studies: (i) what are the rates and impacts of sea level rise and global change on coastal geomorphology?; (ii) how is the coast affected by natural versus local to global anthropic changes?; and (iii) what is the role of biodiversity in the resilience of the system?.

The answer to these questions can only occur through the advance of knowled going hand in hand with the new power brought by technology. This will improve the resolution to observe and simulate coastal processes, thus providing better diagnosis and prognosis and facilitating the implementation of nature-based options to mitigate and adapt to local-global present-future pressures. The dimension of the challenges described below makes it obvious that they can only be successfully carried out through the cooperation among the relevant institutes of CSIC (terrestrial, marine, chemical, atmospherical, etc.) and the incorporation of external actors when necessary.

3. KEY CHALLENGING POINTS

The five iconic ecosystems represent a very diverse set of coastal features (Coastal Lagoon, Estuary, *Ría*, Delta and Mediterranean habitat) with a shared focus on processes at both sides of the land-sea interface. In this section, we describe the key challenges through three big Ds: **D**ynamics of the system, **D**ysfunctionalities resulting from human pressures and **D**efiance to science as a result of these dynamics and dysfunctionalities. The defiance is the core of the challenging point in each system and demands advances in basic science but, owing to the wide diversity of processes and problems these systems contain as a whole, will also offer broad applications to the management of the coast worldwide. Defiances can only be dealt from a wide interdisciplinary perspective due to the very diverse range of the pressures and the intrinsic nature of the coast as the interface between the two realms of the Biosphere: sea and land. However, this interdisciplinary approach should be tailor made to every iconic ecosystem as they represent very heterogeneous situations and pressures are differentially balanced in each one (Table 1). As explained below, it is an ambitious set of challenging points demanding an institutional scale not available everywhere but attainable by CSIC and its close collaborators.

3.1. Guadalquivir Estuary: Coping with uncertainty in support of decision-making

Dynamics

The Guadalquivir Estuary comprises the last 110 km of the Guadalquivir River, 85 km of which are navigable to the Port of Seville, and a morphology that has changed drastically throughout history. It had apparent connections to the mythical city of Tartessos, when it was a large and shallow coastal lagoon known later by the Romans as *Lacus Ligustinus*. Natural sedimentation formed in a very short period (geologically speaking) the present physical environment of the estuary and its surroundings, including Doñana National Park. This resulted in a very flat land that favoured the formation of a meandering estuary with a complex tidal network.

However, the first large-scale human modifications of the estuary began very early, in the XVII century, with the short-cutting of meanders, which progressively reduced the length of the route between the mouth and the port of Seville by 50 km. During the 20th century, agriculture transformed more than 80% of the original marshes connected to the estuary. This represents one of the largest losses of this type of habitat in Europe. Numerous reservoirs were built along the river with a reduction of about 60% of freshwater input into the estuary, and the last one, Alcalá del Río dam, which was built within the tidal river reaches of the estuary, also distorted its tidal dynamics. In concomitance with salt production and aquaculture, these modifications have resulted in an estuary almost completely isolated from its surroundings. As a result, the original and morphologically complex estuary is now a main channel without significant intertidal zones, which is periodically dredged to allow ships to reach the Port of Seville.

Dysfunctionalities

The territory connected to the estuary is home for intense and frequently conflicting stakeholders' interests (port activities, agriculture, aquaculture, tourism, environment conservation, fisheries...). The process of decision-making is difficult in this heavily over exploited environment since it involves several administrative bodies with different competences (environment, transport, agriculture, water policy, etc.) below the regional and national governments, all of them operating under the umbrella of legal instruments of the European Union.

The impacts created by human modifications and pressures in synergy with the complexities of the decision-making process have resulted in an important deterioration of the natural capital of the estuary (Ruiz et al., 2015), with alarming dysfunctionalities mainly involving:

- Extreme values of suspended particulate matter (only surpassed by the Ganges among the largest world estuaries) mainly due to channel deepening and saltmarsh reclamation, which also destabilized the morphodynamics in the estuary, even at short time scales.
- Hyper-turbid waters impede photosynthesis in the water column and the natural functioning of the estuary.
- Hypoxia, anoxia, acidification and hypercapnia affecting the vast majority of its waters.
- Biodiversity loss in a highly sensitive habitat.
- Accumulation of phyto-toxins affecting environmental and human health.
- Reduced capacity to support natural services such as fisheries

Defiances

Conflicting interests around the estuary as well as perturbations in its physical and ecological regime pose a difficult socio-economic context, which led to social alarm when the Port Authority of Seville proposed to deepen the navigation channel by the end of the last century. In 2009, a large team of scientists coordinated by CSIC and the University of Granada presented a comprehensive analysis of the estuary (*Estudio para Diagnosticar y Pronosticar las Consecuencias de las Acciones Humanas en el Estuario del Río Guadalquivir*) and a profound diagnose of its dysfunctionalities.

Ignorance of the functioning of the estuary and the uncertainty inherent to ecosystem dynamics have been pervasive drivers in the history of these human-driven dysfunctionalities. Thus, decision-makers who promoted saltmarsh desiccation after the Spanish Civil War (1936-1939) were ignorant of the decline that this would create on fishery resources. Other actors like port authorities shortcutting meanders and engineers who built the Alcalá del Río dam also did not know that this would mean a dreadful combination for tidal amplification and resuspension of particulate matter. Farmers that changed agriculture procedures several hundreds of kilometres upstream of the estuary could not envisage the severe impact on marine photosynthesis. These are some examples of the many actions undertaken under ignorance that have largely been overcome by the body of scientific evidence in the diagnosis made by CSIC and the University of Granada. The evidence shows the estuary functioning as a whole, from the drainage basin of the river to the oceanography in the shelf at the Gulf of Cádiz. It should be realized that any action from any player in the territory inevitably brings consequences to others (frequently distant) stakeholders. This body of knowledge was consistent enough to substantiate decisions taken by the European Commission, the Supreme Court of Spain and the Spanish Senate.

Despite the accumulated knowledge, no major actions have been undertaken to improve the environmental condition of the estuary and to adapt its uses to global pressures, such as sea level rise over a coastal territory which is essentially flat and further reduction of freshwater supply. Any action will have consequences whose assessment, even with the incorporation of the accumulated knowledge, still will be hampered by the uncertainty inherent to the dynamics of the ecosystem. This uncertainty is not negligible and has the potential to misplace grossly the assessment of the action's consequences. The high natural value of the estuary and its surroundings (e. g. the reserve of Doñana Natural Park), its historical and cultural significance (e. g. Spanish hub for the New World), the importance of the economic activities involved (e.g. agriculture, aquaculture, port activities, tourism or fishery) and the potential societal consequences (home to 1.7 million people clustered in 90 population settlements) are too critical for taking actions, including the lack of action, and actions to improve the current state of deterioration, with uncertain consequences.

The path to reduce this uncertainty is the long-lasting assimilation of powerful observations into state-of-the-art models. This is the method used by meteorologists to reduce uncertainty in weather forecasts, but it is not currently implemented to prognose the dynamics of estuarine ecosystems. The challenge is technological (providing cost-efficient real time observations of physical, chemical and biological variables at adequate spatio-temporal resolution), conceptual (a common frame, where geomorphology, agriculture, engineering, physical oceanography, aquatic ecology or fishery science can be articulated in the models), computational (it is required the architecture for the real-time assimilation of disparate data into simulation models) and societal (by facilitating transparent observations and modelling outputs to the general public). This aim requires an ambitious articulation of trans-disciplinary expertise. However, this expertise is already available at different CSIC institutes together with other institutions which are close CSIC collaborators. By succeeding in this uncertainty-reduction challenge, science will provide more accurate answers to relevant questions the society poses to manage its territory: How will sea level rise affect settlements near the estuary? Should we promote the fishery sector by improving the condition of the estuary? What are the consequences of a new freshwater reservoir? How will biogeochemical cycles change with more tidal connections between the estuary and the surrounding territory? Will this affect to the introduction of exotic species and the ecologic and economic impact they bring? Should we remove the Alcalá del Río dam? Should we further deepen the navigation channel? Thus, by giving precise answers to key decision-making questions, the challenge will help to preserve and restore an highly valuable estuary at the heart of Andalusian cultural identity, and a prototype to be followed by other heavily deteriorated world's estuaries.

3.2. Galician Rias: Securing ecosystem services by promoting the resilience to global change

Dynamics

The Galician coastline extends over 2,272 Km, and therefore is the autonomous region with the longest land-sea interaction zone in mainland Spain. About 60% of the Galician people live in coastal municipalities, which represent only 16% of the total surface area of Galicia. Small-scale fisheries, shellfish extraction from sandbanks, marine aquaculture, and the associated transformation industry impacts on 45 of the 56 economic sectors of Galicia, and represents more than 10% of the GDP. Particularly, 40% of the European and 15% of the world production of mussels are harvested in Galicia. Increasing maritime traffic, recreation, tourism, and nature conservation (e.g. National Park "Illas Atlánticas") also compete for space with the exploitation of living resources. The profound economic, social and cultural relationship of Galicia with its marine environment cannot be understood without the presence of the *rías*, 15 coastal inlets of different size (2.6 to 230 km^2), contrasting settled populations, governing economic activities and thus distinct human print. But, in the end, the high productivity and valuable ecosystem services of these coastal inlets are dominated by the seasonal coastal upwelling during spring and summer seasons[1], which causes the distinctive circulation and nutrient fertilization patterns of the *rías*.

Dysfunctionalities

Climate-related changes in coastal upwelling patterns are the main threats to goods and services provided by the Galician *rías*. Long-term trends in the wind regime over the last decades have been uncertain, with some evidence of a decrease in the frequency and intensity of coastal upwelling (Pérez et al., 2010).

1 The vigorous renewal of the *rías* with deep water (150-200 m) from the adjacent ocean in response to north-easterly winds

Conversely, future climate scenarios predict an upturn of coastal upwelling (Álvarez et al., 2016). Global warming has also produced a trend of increasing sea surface temperature (SST) in the *rías* that will continue over the next decades. The impact of a parallel increase of coastal upwelling and SST on future circulation and fertilisation patterns is unclear and should be examined from two viewpoints: 1) the renewal with well-oxygenated adjacent ocean waters, which guarantees the good environmental status of the *rías* despite their multiple uses; and 2) the carrying capacity, which ensures the role of the *rías* as amazing seafood suppliers. Also linked to coastal upwelling and SST variability is the increasing occurrence of toxic phytoplankton, that threatens the extensive culture of mussels on hanging ropes and the arrival of subtropical fish species that could alter food web interactions and, eventually, the small scale fisheries of the *rías*. Sea level rise is already affecting port and urban infrastructures, shellfish sandbanks exploitation or wetlands preservation. Finally, ocean acidification is particularly important in the Galician *rías* because of the negative impact expected on mussel culture, which likely will not manifest itself until the end of this century because of the carbonate ion oversaturation of the adjacent ocean waters that renew the *rías*. All these climate-related issues act in combination with local pressures such as point and nonpoint source eutrophication (e.g. sewage treatment plants, submarine groundwater discharge), wildfires and subsequent floods that drag the burned soils, urban and industrial pollution or port infrastructures, which vary considerably among *rías*.

Defiances

Global and local pressures will act simultaneously in the Galician *rías* over the next decades displacing these ecosystems from their current environmental status to uncertain deleterious conditions. Can we be secure that the *rías* will continue to provide their essential ecosystem services in the future? Answering this question requires that natural and social scientists work together with local stakeholders (fishers, farmers, port authorities, government departments, conservationists, etc.) to elaborate an adaption plan that secures these services at the medium (year 2050) and long (year 2100) timescales. The strategy must pivot around the known resilience of the *rías* to individual environmental pressures and should be elaborated within the timeframe of the United Nations Decade of Ocean Science for Sustainable Development (2021-2030) proposal on Predicting the Global Coastal Zone: Toward a more Resilient Society (www.coastspredict.org).

This ambitious objective requires an observation programme focused on ameliorating the current knowledge gaps about essential ocean variables (EOVs) that have not been sampled at the appropriate frequency or spatial resolution. High-resolution satellite imagery, fully instrumented buoys and autonomous underwater vehicles (AUVs) are state-of-art technologies that must help to cover some of these gaps. Observation of previously ignored variables or processes (e.g. extreme storms, heat waves, wildfires, turbulent sediment-water column exchange, groundwater discharge, etc.) is essential. It also requires an experimentation programme to cover the existing knowledge gaps about the impact of ignored processes such as heat waves, wildfires, parasites or invasive species in the organisms living in the *rías*, and, particularly, the unexplored simultaneous interaction of multiple climate and local stressors (see chapter 4). Observation and experimentation will feed the third and most critical element of the triad: modelling to produce future IPCC (2016) climate scenarios of the hydrography, circulation and biogeochemistry of the *rías* at the 2050 and 2100 time horizons. Important challenges have to be faced here because currently there are no climate model predictions at the needed resolution to study the *rías* (0.1 km x 0.1 km) and biogeochemical modelling is in its infancy because of the difficulty to model the dynamics of dissolved organic matter and the sediment-water column interactions among other issues. Particularly, toxic phytoplankton modelling is a pending subject despite the occurrence of harmful algae is expected to increase in the forthcoming decades affecting mussel farming and commercialisation.

Modelling outputs will be used to produce future scenarios of the hydrography, circulation and biogeochemistry of the *rías* for at least two climate scenarios: optimistic (SSP2-4.5) and likely (SSP5-8.5). These scenarios will be used to forecast their impacts on small-scale fisheries and aquaculture, tourism, port activities, nature conservation, etc. These forecasting results will feed an analysis of the risks and opportunities that climate and local changes will have on the *rías* by 2050 and 2100 under the two climate scenarios chosen. This is a key activity where natural and social scientists have to interact to produce the nucleus of the adaptation plan of the Galician *rías* for the rest of the century. Next, and final challenge, is that social scientists make a detailed economic assessment of the risks and opportunities previously identified as well as of the measures suggested to secure that the *rías* will continue to provide their ecosystem services in the future. Stakeholders are essential in all this process providing their experience, data and feedback. So, a good strategy to involve stakeholders of the coastal and maritime areas is key to increase scientific acceptability (credibility), policy relevance (salience) and social robustness (legitimacy).

Producing an action plan for the 15 Galician *rías* is not feasible in the time frame of a decade and considering the human resources available. The effort should concentrate first in the Ría de Vigo, where the CSIC Institute of Marine Research is based, during a period of 5 years that would be a pilot study with the potential to be exported to other coastal areas worldwide. In fact, in the 5 years after the study of the Ría de Vigo, specific action plans could be prepared for two more *Rías* Baixas, Arousa (the *ría* of the 2,300 mussel rafts) and Muros (the least anthropized inlet) and at least the largest of the *Rías* Altas (Ares-Betanzos).

3.3. Ebro Delta: Sediment management, from basin to local scales, for the preservation and progressive adaptation to future scenarios

Dynamics

The Ebro Delta is the third largest delta of the Mediterranean Sea, with an area of 325 km^2. It supports fundamental ecological functions of wetlands and has a high economic, cultural, scientific, and recreational value. The deltaic ecosystems are of high significance and they include sandy shores, dunes, salt marshes and lagoons providing habitat for high biodiversity. The area is a designated Natural Park in Spain and protected under the EU Birds and Habitats Directives and biosphere reserve by UNESCO.

The huge amount of sediment supplied by the Ebro River during the past thousands of years has allowed the development of the present delta plain and the submerged prodelta. The most recent deltaic deposit is made of several prograding sequences of superimposed delta lobes that were developed due to successive channel switches on the delta plain during the last millennium. Other than the present river mouth, traces of four ancient river mouths and their respective lobes can be found on the delta plain or in the inner shelf. Over time, river avulsions and the change in the location of the river mouth are accompanied with a rapid progradation on the new delta lobe because the deposit of river sediments, and a fast erosion of the abandoned lobe by waves and alongshore currents. In the 1930s, a new river mouth opened to the north of Cape Tortosa, and has progressively become the main sediment discharge outlet. This last change in the river mouth position led to severe coastal retreat (ca. 2500 m between 1947 and 2014) at the abandoned river mouth (Cape Tortosa). The eroded sediment has been transported towards the SW and has helped with the maintenance of this sector of the delta.

Dysfunctionalities

Human management of the river has dramatically reduced the water flow as well as the sediment discharge during the last century. Large dam construction since the 1960s in the lower Ebro drainage basin has favoured the sediment retention in water reservoirs, the regulation of river floods (that are events with the maximum sediment transport) and also favoured water consumption. At present, the limited amount of sediment supplied by the river is unable for a significant progradation in the river mouth as occurred in the past. In addition, the delta plain is now regulated by a complex system of irrigation channels that prevent floods and overspilling and only supply a small amount of sediments to the delta plain.

In the medium and long-term perspective, the sedimentary deficit effects are strongly intensified by the relative sea level rise affecting the delta plain. Effects of subsidence and sea level rise caused by climatic change are around 3 mm/yr each one of them, but the sea level rise rate is expected to increase during next decades. Therefore, huge amounts of sediments would be required to compensate the > 6 mm/yr drowning of the delta plain.

The fragility of the deltaic system was evidenced during the Gloria storm-surge (January 2020), which caused the flooding of large deltaic areas and strong landward retreat of the shoreline. Furthermore, after the storm, the natural resilience of the system in some areas (Trabucador Bar, Buda Island) was extremely slow, suggesting that these impacts could be irreversible in the near future.

Most of the deltas around the world have similar problems as the Ebro Delta, with an increase of their vulnerability as a result of subsidence, the trapping of sediment in reservoirs upstream and floodplain engineering in combination with rising sea level (Syvitski et al., 2009). Problems caused by erosion and flooding in the Ebro Delta are known for the last 30 years and many studies and protection plans were prepared. In spite of the different integral conservation plans and, in general, of the good scientific knowledge of the system, no general actuation for the delta preservation has been launched.

Defiances

The interaction between the shortage of sediment supplied by the river, the local subsidence, the natural sediment redistribution along the delta, and the sea level rise can induce the disappearance of the Ebro Delta in a relatively short period (a few centuries?). However, the exceptional environmental singularity of the Ebro Delta as well as their relevance for the economy of the region (tourism, fisheries, aquaculture, agriculture) deserve a great effort for its preservation and it is a thrilling challenge for the scientific community.

The diagnosis of the current situation in the Ebro Delta indicates that the sediment deficit is the fundamental reason of habitat losses and vulnerability and, consequently, the optimization and comprehensive management of the sediment becomes a crucial issue to address in order to avoid its disappearance. Thus, the research challenge focuses *on the sediment management, from basin to local scales, for the preservation and progressive* adaptation of the Ebro Delta to future scenarios.

An integral sediment management should include an accurate estimation of the sediment availability and their characteristics, the location and the estimation of areas with sedimentary deficit, the research of new methods to increase the amount of sediment supplied to the delta and the optimization of the redistribution of the available sediment. In addition, the application of this management should consider the social priorities of the people living in the delta. Sedimentary needs can be divided into two types: sand and mud. The sand is a priority for the coastal zone (beaches, dunes) while the mud is a priority to counterbalance the sinking of the delta plain. The main demands to answer this challenge are:

- The shape of the Ebro Delta coast is mainly caused by the alongshore sediment transport dominated by waves coming from the eastern sector. Beaches and the nearshore are composed of sand which is transported alongshore and finally deposited in the tail of the two spits developed on both delta sides. Thus, losses of sandy sediment from the deltaic system mainly occur off shore and during overwash events. The research should include an accurate analysis of the sediment budget of the different sectors along the Ebro Delta in order to calculate the excess or shortfall of sand in each section and to plan potential sand transfers. A reasonable coastal evolution and flooding model, beyond the simplistic "bathtub" model usually applied, should be developed for the decadal analysis of coastal evolution.

- The lower Ebro river transports small amounts of sand as bedload (roughly about 15000 T/yr), usually in the form of dune or megaripples migration. This sediment comes from the drainage basin outside of dam regulations and from de erosion of the river bed. Since the amount of bedload depends of the near-bottom flow velocity (and water discharge), the research should focus on the increase of sediment transport using short periods of high water discharge (700-1000 m^3/s) as small flushing flows and in the characterization of bedforms dynamics during these periods.
- Several large dune fields are located along the Ebro outer continental shelf, at ~90 m water depth. These dunes were developed during the early stages of the last sea level rise (around 12000 years ago). They correspond to a relict, limited, non-renewable sand resource that only should be used during extreme situations. However, an evaluation is required of the volume and characteristics of these sandy deposits, as a strategic potential resource for eventual future restoring actions. For muddy sediment, the potential use of accumulated sediment in the Alfacs and Fangar bays should also be investigated.
- It is estimated that more of 100 x 10^6 tons of sediment have been accumulated in the main reservoirs of the lower Ebro River during the last 50 years (Riba-roja and Mequinenza). The sediment accumulated in such types of reservoirs is considered as a "resource out of place" (Kondolf et al., 2014), because it is not needed in the reservoir, but downstream. Taking advantage of part of these sediments to counteract the sediment deficit in the Ebro Delta is a scientific challenge. The research should include an accurate evaluation of the amount and quality of the available sediment and the analysis of different strategies for the removal and bypass of sediment until their arrival to the delta plain (dredging, sediment bypass tunnels, flushing flows, sluicing, ...). The application of any of these methodologies implies a complex coordination between the sediment management, hydropower operations, water reservoir management and the derived ecological, agricultural and touristic issues. Nevertheless, re-establishing (even partially) the sediment flux continuity along the river is the most sustainable form of favouring the maintenance of the delta plain.
- The adaptation of the Ebro Delta to future scenarios will also require additional innovative solutions of sediment management. For instance, the "production" of bioclastic sediment from vegetable remains or generated by *Posidonia oceanica* meadows in the coastal zone are both promising nature

based possibilities. The design of small dunefields for trapping eolian sediment, the use of the accumulated sand in the backshore after flooding or alternative ways to use the sediment for the protection of the coast could help to the maintenance of deltaic coastal ecosystems.

3.4. Mar Menor: Water and nutrient interchanges of the lagoon with the continental basin and the Mediterranean. Sea level rise

Dynamics

The Mar Menor is a lagoon located in the SE of the Iberian Peninsula. It covers 135 km^2 and has an average depth of 4 m. In the Mar Menor area the annual rainfall is < 300 mm and the potential evapotranspiration > 1300 mm; with the water interchange with the Mediterranean limited, the lagoon is hypersaline.

The watershed had no permanent watercourses. The uppermost Quaternary aquifer is the only one having hydraulic contact with the lagoon. During the natural regime, there was no surface water discharge except during heavy rains and the volume of groundwater discharge should be low and with a very low nutrient concentration. Though the nutrient discharge is higher during floods, soils were not nutrient-rich, and inorganic fertilization is, historically, recent. The agricultural landscape was dominated by drylands. The result of this natural regime was a low nutrient input into the lagoon and as a consequence, marked oligotrophic conditions.

High salinity, an oligotrophic state and large within-year temperature range as a product of its confinement conformed singular ecosystems. Benthic communities were dominated by euryhaline and eurytherm organisms, including macrophytic communities of typical eurybiontic seagrass species (*Cymodocea nodosa* and *Ruppia cirrhosa*). The inlets between the sea and the lagoon allowed seasonal migrations of fish populations for reproduction and a local fishery highly valued by the quality of its products.

Dysfunctionalities

The irruption of novel economic production systems from the 1950s forced accelerated changes in the Mar Menor. The first factor was tourism focusing on the coastline, although since the 2000s it expanded building resorts all around the watershed. Tourism produced loads of urban sewage discharge, a problem mostly solved in the mid 2000s. Natural shores of the inner coastline were replenished creating artificial beaches. Sediments were obtained from dredging the lagoon, and retained with rock groynes, which, together with wetland destruction, had an overall significant impact on the ecosystem. The regulation of the Segura river reduced the sediment availability for the barrier sandbar and its urbanization disrupted natural sand deposition cycles. One of the inlets was enlarged for the transit of recreational boats, increasing the turnover of lagoon water and decreasing its salinity (from >50 PSS to 42-46 PSS), triggering the invasion of species with a lower tolerance to salinity. There was a sudden spread of the opportunistic clorophyte *Caulerpa racemosa* throughout the entire lagoon. In its expansion not only the lower salinity but the increasing nutrient loads could have played a role. Jellyfish outbreaks of species like *Cotylorhiza tuberculata* and *Rhizostoma pulmo* started to be frequent in the lagoon.

In the 1960s-1970s the expansion of irrigated agriculture was supported by groundwater exploitation. In 1979 Tagus to Segura water transfer began and since then irrigated land has multiplied by ten. Part of this increase occurred out of the areas authorized to be irrigated. Other water resources are wastewater reuse, seawater desalination and groundwater, the latter being the main buffer for Tagus transfer oscillations. Intensive irrigated agriculture neglected soil conservation measures. The expansion of irrigation increased groundwater recharge and its discharge into the lagoon and the agricultural intensification polluted groundwater with nitrate. Groundwater is brackish and farm-sized desalination plants were installed and the nitrate-rich brine produced was poured into the lagoon. The land transformation increased on-site runoff and sediment production and the connectivity of the local flows released a high nutrient load into the lagoon during heavy rain events. Flash floods are a major source of phosphorus. Increased nutrient input into the lagoon was apparently buffered by benthic macrophytic meadows. In 2015 a phytoplankton bloom occurred reducing light availability at the bottom producing 85% loss of benthic vegetation loss, in turn exacerbating nutrient imbalances and phytoplankton growth. In September 2019 a heavy rain produced an estimated discharge of 60 hm^3 into the lagoon and very high loads of nutrients. Water stratification by salinity and minimal mixing under a long anticyclonic situation produced anoxia and massive mortality of sessile organisms. Later, winds produced an upwelling of bottom anoxic water killing large numbers of fishes on the beaches and producing a deep impact on local, national and even international public opinion.

Defiances

The concentrated pressures of multiple human activities in the Mar Menor are typical of coastal areas worldwide. Feedback mechanisms such as those linked to benthic macrophytes and coastal wetlands dampened the effect of the pressures, but the capacity of such mechanisms was surpassed in 2015-2016. Based on current scientific knowledge, such eutrophication induced ecosystem shifts can probably last for decades if no mitigation and reversion measures are adopted. These measures should be science based and considering all the socioeconomic complexities of the system.

Sea level rise caused by global warming threatens the barrier sand bar, which is unable to adapt to new conditions and can be a serious risk for people and goods and the integrity of the lagoon itself during future extreme storms. The eutrophication process and the possibility of reversion by the internal dynamics of the lagoon are not yet well understood. Sea-lagoon interchange is a major issue in this topic. At the present an intense debate is occurring about the opportunity of enlarging the communication with the sea to increase water turnover rate and facilitate the export of nutrients to the open sea, but the former decrease of the lagoon salinity affected its singularity, natural values and fishery.

There is uncertainty on estimation of groundwater discharge. Whichever the real figure was, the main baseline nitrate input into the lagoon is by groundwater either in the shore or routed through the drainage network. To address the problem infrastructures, groundwater coordinated pumping, technology to denitrify groundwater and artificial wetlands are being proposed. All of these are ex post actions, more emphasis should be given to research ex ante actions: (i) how to regulate irrigation to meet crop demand but minimize deep percolation; (ii) how to regulate fertilization to minimize nitrate losses to the aquifer. The relationship between rain events and irrigation and fertilization and its effect on groundwater recharge and nitrate percolation is an important link and new techniques of smart agriculture taking into account weather forecasts at different time scales are necessary. Flash floods are also a major source of nutrients. Water flow meters at the outlet of the drainage network do not inform the spatiotemporal distribution of runoff/sediment sources, a critical aspect for the parametrization of hydrological models and even more important to understand the key point of landscape connectivity to water and sediment flows. Complex observation networks are necessary. The research of landscape structure and organization from the plot to watershed scale and the minimization of its connectivity are a priority.

3.5. Balearic Islands: Reconciling recreational use (tourism) with ecosystem preservation under global warming

Dynamics

The Balearic Islands are an archipelago in the western Mediterranean Sea, with Mallorca, Menorca, Ibiza, and Formentera as the four largest and inhabited islands. Between them the Balearic Islands have a shoreline length of 1,723 km. This isolation from the mainland brings an associated high ratio of coastline to area and the lack of year-round river runoff.

The most important marine ecosystem along the coastline are seagrass beds. As one of the most productive ecosystems on Earth, seagrass meadows oxygenize the water column and reduce nutrient and organic loading. They also provide habitat and function as nurseries for numerous fish and invertebrate species through their structural complexity. Flexible seagrass canopies can attenuate waves but foremost stabilize sediments, thus preventing excessive coastal erosion while also, in absence of significant continental sedimentary inputs, seagrass meadows provide carbonate sediments to many balearic beaches.

Through their carbon uptake and subsequent burial and storage of organic matter in the sediments under the meadows, seagrasses can be a major element in climate change mitigation as seagrasses are globally significant carbon stocks. A total of six seagrass species are present in the Mediterranean basin, with *Posidonia oceanica* as the most important as well as endemic seagrass species of the Mediterranean Sea, forming meadows extending from the surface to 40–45 m depth. *P. oceanica* meadows in the Balearic islands make up for 50% of the Spanish surface inventory and cover a surface of over 650 km^2. In the last twenty years, *P. oceanica* has become one of the main targets of the protection and management of the Mediterranean marine environment. Parallel to EU legislation, each EU Member State evaluates the health status of *P. oceanica* meadows according to the Water Framework Directive (2000/60/EC), while on a regional level, the autonomic community of the Balearic Islands' decree 25/2018 specifies detailed conservation objectives.

Dysfunctionalities

The Balearic Islands are one of the most important "sun and beach" tourist destinations in Western Mediterranean. They receive around 13.6 millions of tourists each year. The Balearic Islands coast and their beaches have an iconic status in the tourism economy and in the inhabitants' culture and way of life. Tourism and recreational activities exert a significant pressure on the coast. It has been estimated that each ha of the beach surface produces 16,537 €/month just in terms of recreational service. Therefore it is not difficult to envisage the pressure on the coast that destroys coastal dune systems or build groins and recreational harbours along the coast. By means of groins and recreational harbours, the sedimentary cellular system is altered and the sediments mass balance is unbalanced generating beach accretion at some points of the beach and erosion in the opposite ones. Currently, there is no regional study addressing shoreline evolution on a long-term scale, which indeed is critical under the sea level rise scenario. The medium-term changes in beach systems reveal that in the Balearic Islands the coastline exhibits a great variety of shoreline trends with a general equilibrium in shoreline (only 1.2 % of beach present medium term retreats larger than 1.5 m/yr). There is no clear spatial pattern in eroding, accreting or stable beach distribution.

Even though many protective measures are in place, seagrass habitats like *Posidonia oceanica* are declining (Waycott 2009), and even while some seagrass species seem to recover, this is not the case for *Posidonia*. Between 1965 and 2015 a loss of cover extent of 34% has been estimated for the Mediterranean basin (Telesca et al. 2015), with an annual regression of 6.9% over a similar period for the Balearic Islands. This demise has been partly attributed to basin scale changes such as rising temperatures and invasive species but anthropogenic pressures like physical disturbance (anchoring, trawling) and contamination by wastewater (nutrients, organic matter) and fish-farms are important local pressures on seagrass meadows associated with the increased usage of coastal areas. Given the slow growth and reproduction rates of *Posidonia*, recovery could take centuries to millennia, and is thus insignificant on a human time-scale. Therefore, it is crucial to detect signs of disturbance early on in order to take preventive action and minimize the long term effects of local disturbances on these meadows.

Defiances

Global change, including sea level rise, will produce significant changes in the dynamics of coastal seas around the world and the Balearic Island coastal system is not exempt from them. The first impact under this scenario is the change in the storm regime and the consequent wave climate. Beaches are the equilibrium result of waves distributing available sediment in a geomorphological frame. If one of the drivers changes, as wave climate is expected to do, the equilibrium of the beach will change accordingly (both in its profile as well as in its planform) to dissipate the energy from the incoming waves.

Physical impacts of sea level rise along the coastlines are only expected in the long-term (decadal and longer time scales). In sedimentary coasts, these are likely to include permanent inundation of the low-lying sectors. However, besides these long-term effects, major immediate climate-related impacts of sea level rise along the coastlines occur due to the increased likelihood of extreme sea-level events as these reach the coast on top of higher sea levels and are therefore potentially more hazardous. Extreme sea levels arise from the combination of tides, storm surges and waves. Thus, changes in storminess will also be affecting storm surges and waves as well as their effects along the coasts. However, the effects of waves on beaches are largely determined, not only by the wave height and period, but also by their incident direction. In this respect, earlier works have found significant changes in projections of wave direction as a result of a shift in atmospheric conditions under climate change scenarios. Vulnerability assessments or any suggested measure might be inaccurate unless all the processes driving sea-level change and storminess at the regional/local scales are fully understood and considered in an applied context

Rising atmospheric CO_2 is driving ocean warming, particularly in the enclosed Mediterranean. *Posidonia oceanica* shoot mortality will be enhanced when critical temperature thresholds are exceeded, synergies with local pressures need to be evaluated under this scenario to establish future trajectories for *Posidonia* meadows and to predict if more temperature robust species like *Cymodocea nodosa* are capable to replace important ecosystem functions. Due to increased niche suitability caused by warming, the progress of invasive species can be facilitated by increased marine traffic as an important vector and this potential threat to coastal ecosystems should be monitored. Long-term monitoring series can provide insight in demographics.

Apart from warming, another effect of increased atmospheric CO_2 is direct uptake by the ocean and associated lower pHs (Ocean Acidification; OA. As OA is mostly a threat to the colder (deeper) areas of the Mediterranean and other factors play a big part influencing coastal pH/pCO_2 dynamics, the Balearic coastal region is an excellent laboratory to monitor variability due to i.e. metabolic activity (PP) of marine plants and freshwater runoff associated to precipitation.

Managing protected habitat (*Posidonia* meadows) taking into account the impact of recreational use (i.e. anchoring, contamination through wastewater effluent), which is related to the economic motor of the region, should be done by recognizing and integrating ecosystem services of seagrass meadows (i.e. like Blue Carbon) into policy. For instance, apart from recognizing the role of marine vegetation in climate change mitigation (Blue Carbon), its role as protector against erosion of the seafloor and of beaches (beach wrack, wave attenuation, protection against erosion) and the amount of sediment produced should be quantified and integrated into policy.

The involvement of the public is crucial to create a base of support for conservation measures and necessary to guarantee successful reinforcement of existing measures. In these times where information reaches the public over social media fast, it is possible and important to engage and mobilize the public in scientific questions and bring science to the people (citizen science) as a means of raising awareness and commitment for preservation of the marine environment.

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CHALLENGE 8

ABSTRACT

Oceans are no longer inaccessible places for data acquisition. High-throughput technological advances applied to marine sciences (from genes to global current patterns) are generating Big Data sets at unprecedented rates. How to manage, store, analyse, use and transform this data deluge into knowledge is now a fundamental challenge for ocean sciences. Artificial Intelligence and Machine Learning are the most promising and exciting approaches addressing this challenge. These technologies are directly applicable to many data analysis problems and major challenges in the study of the ocean microbiome, ocean observation and forecasting, animal biology, ecology and conservation, resource management, and marine geosciences. We are only at the beginning of an era when machines are able to solve complex tasks that, until today, have required human expertise. We envision that the combination of ocean Big Data and Artificial Intelligence will provide the means for ground-breaking advances in our understanding of ocean functioning.

KEYWORDS

high-throughput sequencing

marine conservation | deep-learning

data-driven | zettabyte | biobanks

animal-tracking

CHALLENGE 8

OCEANS OF BIG DATA AND ARTIFICIAL INTELLIGENCE

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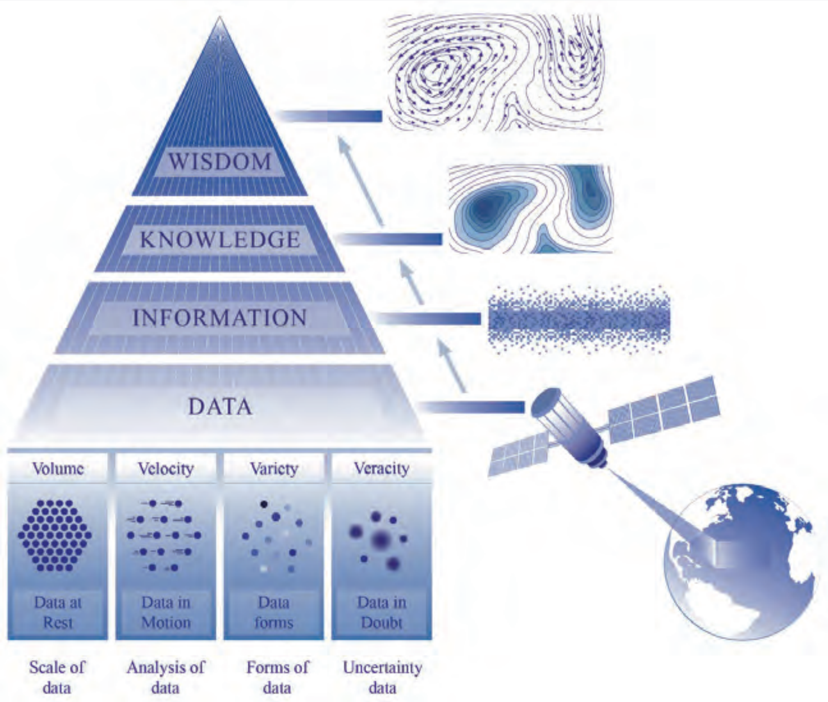
1. INTRODUCTION AND GENERAL DESCRIPTION

Data are produced when abstracting the world into measures or categories (numbers, characters, images) and are the basis to generate information, knowledge and ultimately wisdom (Kitchin 2014, Fig. 8.1). Data are symbols that represent facts, e.g. temperature records. There is no meaning of data beyond its own existence and can be clean, noisy, structured, unstructured, relevant, or irrelevant. Information can be considered as data that have been processed and that then become useful. In other words, information adds meaning to data. Knowledge can be considered as the application of information and data or the "know-how" that transforms information into instructions. Wisdom is the pinnacle of the knowledge pyramid and refers to being able to apply knowledge (Fig. 8.1).

During the last decades, the capability of humans to generate data has increased exponentially, leading to the so-called Big Data. Even though there is no formal definition of Big Data, it usually is characterised by the **4Vs: Volume, Velocity,**

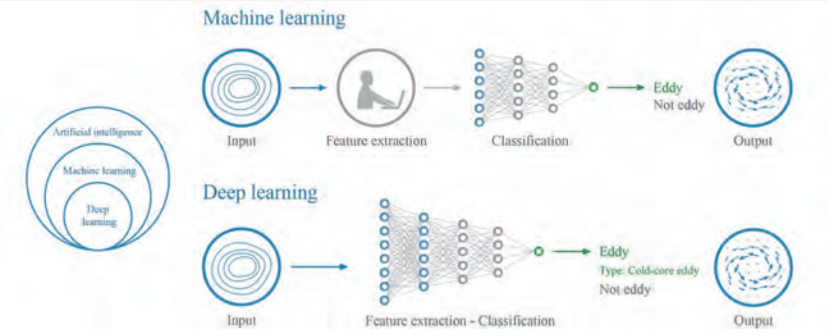
FIGURE 8.1–The DIKW or Knowledge pyramid, and the characteristics of Big Data applied to ocean science.



Variety, and **Veracity** [Fig. 8.1] (Kitchin 2014). Quantifying the **volume** of global data at the moment is not straightforward. According to the International Data Group's study – "The Digital Universe in 2020" (https://bit.ly/3b4xgyy), the amount of data in the year 2020 would be ca. 40 trillion gigabytes (or 40 zettabytes). Interestingly, most data has been generated during the last two years and, by 2020, every person was predicted to generate 1.7 Mb per second (https://bit.ly/3fjEQsH), or 146,880 GB a day, leading to a production of 165 zettabytes per year by 2025 (https://bit.ly/3b4xgyy). In particular, ocean sciences have also experienced an explosion of data during the last decade (Brett *et al.* 2020; Guidi *et al.* 2020). Examples are the DNA sequencing of the ocean microbiome, which has produced a few hundred terabytes of raw data since 2010, or the first world's ocean digital map of seafloor lithologies based on descriptions of nearly 14,500 samples. Small data differs from Big Data in terms of the **velocity** at which it is generated. Big Data tends to be generated continuously, in many cases, in virtually real-time. For example, satellites continuously stream ocean observation data and weather sensors monitor and transmit weather conditions so their data can be ingested in weather forecasting. Such a continuous stream of data needs continuous management and analysis (Fu *et al.* 2019). In addition, Big Data can display **variety**. That is, it can be a combination of structured, semi-structured or unstructured data, including numbers, text, images, videos and audio, which can be combined. It is widely acknowledged that ca. 80% of Big Data is unstructured. New advances in high-performance computing, database design using Not only Structured Query Language (NoSQL) formats and data mining have allowed to store, manage, process and extract knowledge from unstructured data. Finally, data **veracity** defines, not only how accurate a Big Data set may be, but also how trustworthy the data source, type, and processing is. Removing biases, inconsistencies, duplication, and volatility are just a few accuracy factors of data, which in the context of Big Data becomes a real challenge. Veracity issues in marine sciences arise, for instance, due to the stochastic properties of data-process generation, manual entries, GPS uncertainty, or by model uncertainties in ocean forecasting processes (e.g., hurricanes). Strikingly, most Big Data sets seem to remain unanalysed, with estimates ranging from 97% to 99%. Nevertheless, we need to consider that only a fraction of Big Data may be useful: in 2012, only about 23% of Big Data was considered useful (https://bit.ly/3b4xgyy). Recently, the Science Brief of the European Marine Board has included the **value** of the data as a new dimension of Big Data in marine sciences. Understanding the costs and benefits of collecting and analyzing data is therefore needed to ensure that its value can be reaped (Guidi *et al.* 2020).

The ocean covers ca. 70% of the surface of the planet and contains ca. 97% of all water on Earth. It plays a central role in regulating the Earth's climate system, and its physical, geological and biological processes play a key role in global biogeochemical cycles (see chapter 2). Due to its importance, a wide array of monitoring efforts have been implemented, including *in-situ* (e.g. gliders, Argo floats, buoys, OBSs (Ocean Bottom Seismometers), Seafloor Observatory Systems) and *ex-situ* (e.g. satellites, drones) sensors covering different spatial and temporal scales (see Chapter 1). Technological advances in sensor technology, autonomous devices and communications allow us to collect Big Data from the ocean in a continuously increasing way. Thus, in

FIGURE 8.2—Artificial Intelligence, Machine Learning and Deep Learning applied to the pattern identification of swirling motion of eddies in the ocean



agreement with the 4 Vs of Big Data, the generated ocean data occupies huge volumes, it is collected continuously in virtually real-time and features variety (i.e. it is unstructured and may consist of images, numbers or DNA sequences). Our capability to generate Big Data from the ocean contrasts with our capacity to analyse them, which has not advanced at the same rate, becoming a bottleneck for the generation of information and knowledge (Malde *et al.* 2019). Recent developments in Artificial Intelligence (AI), in particular Deep Learning (DL) are now allowing processing Big Data and generating new insight (Guidi *et al.* 2020).

AI is broadly defined as "the study of agents that receive percepts from the environment and perform actions" (see White Chapter on Artificial Intelligence). Machine Learning (ML) is a branch of AI (Fig. 8.2) that aims at "iteratively evolve an understanding of a dataset; to automatically learn to recognise complex patterns and construct models that explain and predict such patterns and optimise outcomes". ML approaches can be supervised (using training data) or unsupervised (using self-organization). Supervised learning involves a model that is trained to match inputs to known outputs, while in unsupervised learning, the model teaches itself to find patterns in the data without the use of training data (Kitchin, 2014). In both cases, a model is generated via a learning process that is modulated by rules and weights. The construction of the model starts simple, and then it evolves into a robust one after changing repeatedly.

Deep Learning (DL) is a subset of ML (Fig. 8.2) that uses multilayer artificial Neural Networks. Traditional ML requires substantial human effort in defining features that represent data, while there is no need to define features in DL, as DL learns the best representation of the data itself in order to produce the most accurate results. DL algorithms require Big Data, and their efficiency improves as more data is added. This contrasts with classic ML approaches that reach a plateau at some point, no matter how much data is added. Another advantage of DL algorithms is that they can represent complex non-linear separating functions, and this is ideal for tasks that require learning complex concepts. Furthermore, feature identification is not required, minimising the chance of human biases. In addition, DL can take advantage of massive parallel processing, as in GPUs, to learn better models.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Big Data coupled to AI will revolutionise ocean sciences (Malde *et al.* 2019). Right now, marine sciences are rapidly evolving towards massive data generation from automatic sensors thanks to the increase in computational power and the development of new technologies (Brett *et al.* 2020). High-throughput sequencing, animal and human (e.g. vessel monitoring system) tracking, ocean observing from local stations to satellites, seismic, acoustic, geophysics and sediment data are major examples of how marine sciences are entering into a new Big Data era. How to manage, store, analyse and transform the oceans of Big Data into knowledge is now a fundamental challenge for ocean sciences. This challenge can only be addressed by changing the paradigm in marine sciences, from traditional model-driven representations (e.g. data assimilation in physical and biological models) towards accurate and computationally-efficient data-driven models. AI integration in marine sciences is, without any doubt, the only candidate to bridge this gap. DL is particularly well-positioned to infer data-driven dynamical priors and associated assimilation schemes. However, the integration of AI will need cross-disciplinary expertise at the interface of marine sciences, applied mathematics, and computational sciences to upgrade the current trend of simulation, mapping, forecasting, and assimilation models and technologies towards a novel scientific paradigm bridging the physical, geological and biological paradigms underlying marine sciences and the statistical paradigm on which AI and ML are based. The integration of DL neural networks in marine sciences is in its infancy. However, it will benefit a wide range of, or almost all, oceanographic fields (actively used so far only in the processing of partial satellite data, animal tracking, classification or measure, and assembly and annotation of high-throughput DNA sequencing data). This novel paradigm will fully benefit from AI-related technological advances to build the next generation of ocean, atmosphere, and climate simulations, mapping, forecasting and reconstruction (assimilation) models. Within biological applications, similar expertise is needed for an effective shift of how field estimates of abundance or species composition are made, as well as for automatization and unsupervised acquisition of long-term time-series of ecological data and processing based on real-time and lagged-time video analysis from underwater sampling devices. Further, for marine conservation (e.g. automatic fish length estimates at the commercial landings, automatic boat detection inside marine reserves), AI-based applications are being developed (Brett *et al.* 2020). Big Data coupled to AI will also revolutionise the field of bioprospecting & blue biotechnology via automated detection of compounds/genes with economic potential (Guidi *et al.* 2020). In addition, early warning systems based on AI and ocean Big Data will likely allow mitigating the effects of ocean events, such as red tides or the outbreak of pathogenic bacteria or viruses. Overall, all fields of life are experiencing a technological revolution due to AI. Oceans, their understanding, function and conservation, have the challenge to incorporate AI in the next decades.

In the smart oceans of the future, it is expected that data that are currently treated independently, such as satellite, genetic, animal tracking, or acoustics, will be jointly analysed using AI by autonomous supercomputers. AI analysis of these massive amounts of data will allow us to discover patterns as well as to provide a detailed and real-time global perspective of the ocean across multiple spatiotemporal scales. Also, AI will help to automatize seafloor mapping and increase the capabilities of the interpreters. Likewise, Big Data analyses together with models and simulations will significantly increase our ability to predict events at multiple scales, from the evolution and spread of a virus and its effects on trophic networks, to the positioning, development and health status of hundreds of millions of fish over time, as well as their relationship with biogeochemical processes or the ocean microbiota. Furthermore, these analyses will generate a renewed holistic insight and understanding of the ocean, being also the base for new conservation policies and applications leading to new products and promoting the Blue Economy in line with EU policies (https://ec.europa.eu/maritimeaffairs/policy/blue_growth_en) and United Nations Sustainable Development Goals (https://www.undp.org/content/undp/en/home/sustainable-development-goals.html).

3. KEY CHALLENGING POINTS

Even though AI-based and data-driven frameworks will certainly lead to major breakthroughs in marine science, the state-of-the-art for numerous applications and domains strongly relies on model-driven approaches (e.g., simulation and assimilation frameworks in operational oceanography) using the physical knowledge and associated mathematical representations of geophysical and biological dynamics gained over the past centuries. A major challenge is to bridge the model-driven and AI paradigms to make the most from the current knowledge in physics, biology and geology coupled to the increasing computational efficiency and discovery capability of AI methods as well as the explosion of Big Data. In particular, the advent of Big Data urges researchers for Data Management Plans (DMPs), that will determine, among other things, how data is shared in the scientific community, how it is stored over long periods (e.g. decades) and how it is accessible to the general public, stakeholders and policymakers. With the objective of making research data Findable, Accessible, Interoperable and Re-usable (FAIR), DMPs are key *obligatory* elements for Horizon 2020 EU projects, describing the data management life cycle for the data to be collected, processed and/or generated by marine research projects. Possibly, during the next few years, other funding agencies will require DMPs, such as the Spanish AEI (Agencia Estatal de Investigación).

At this point, we identify three general challenging points that are associated with the generation, management and analysis of ocean's Big Data:

Big Data Generation. Currently, there are a multitude of applications and sensors that are generating Big Data from the ocean in different research areas (Brett *et al.* 2020). For example, satellites, research vessels, buoys, gliders, animal tracking devices (see Chapter 1), AI-processed images, DNA sequencers. Some of these sensors may generate continuous data streams that need to be processed in virtually real-time in order to generate useful outcomes (e.g. ocean forecasting). Other sensors or devices will produce massive amounts of data in a more discrete manner, such as DNA sequencers. As mentioned before, our capabilities to produce Big Data are increasing exponentially, as well as the number of interconnected devices that collect data (the so-called internet of things, IoT). Thus, at the moment and considering the future perspectives, data production *per se* does not seem to be a big challenge. Yet, the challenge is probably related to producing new types of Big Data or datasets that can lead to useful insights. Thus, instead of increasing the data production capacity of current sensors, the development of new sensors or new data-collection strategies may lead to new types of Big Data. For example, microsensors attached to millions of fish or high-frequency *in-situ* -omics samplers could generate datasets that could provide new knowledge of animal movement or gene function.

Big Data Management. The main challenges are related to data storage, transfer, integration and computing. As for Big Data storage, it must have Petabytes size scale, be highly scalable and flexible due to the need to increase its capacity under demand, and have low latency for real-time access. This storage must be accessible across multiple platforms and systems and be able to handle data from various source systems at the same time. Another aspect that needs to be considered is the Big Data long-term storage and its associated costs: it is becoming evident that storing huge amounts of data over long periods may have substantial costs. Furthermore, Big Data that today has low value could become priceless in the future, therefore, coordinated actions need to be taken in order to reach an agreement on how Big Data will be stored and made available for the next decades. Another specific challenge is related to the real-time transfer and access of Big Data: today, large amounts of data need substantial time to be transferred from one site to another or accessed by different applications, generating a delay in the analyses that could prevent their use in decision-making. Moreover, our capability to efficiently analyse an exponentially increasing amount of Big Data also represents a challenge for the next decades, as the increase in computing power is lagging behind our capabilities to generate Big Data. Thereby, the importance of current research in new computing architectures tailored to the needs of Big Data. Cloud computing technologies can provide suitable scalable solutions (Vance *et al.* 2019), not only to configure *ad-hoc* hardware resources for analysis, but also as data storage. These two characteristics combined may put data and computing in the same place, thus reducing data transfer delays.

Another particular challenge is related to the integration of Big Data from different sources (-omics data, satellites, acoustics, etc.). Currently, datasets from different sources are normally analysed separately (e.g. omics data and satellite observations), thus precluding holistic insights that would emerge from the combined analysis of these datasets. This requires the use of new computational models for the analysis of massive data, such as MapReduce, and new data storage models such as new file systems, NoSQL databases and in-memory Databases.

Big Data Analysis. The massive amounts of unstructured data that are being generated need new methods to analyse them. AI methods, especially neural networks (DL) are currently the most promising tool for analysing ocean Big Data. At the moment, researchers from different fields are migrating into AI-based analyses and this trend will likely increase dramatically during the next decade. AI-based analyses of Big Data represent a breakthrough in diverse fields, such as marine observatories, early detection systems and image analyses. AI will also be pivotal for new autonomous devices, such as gliders or even ships, where decisions will be taken without human supervision. A fundamental aspect here will be the validation of the decisions taken by the AI, and the potential costs that bad decisions may have.

These three "grand challenges", that is, Big-Data Generation, Management and Analysis (GMA) are encountered (normally together) in different fields of science. Below, we indicate how Big-Data GMA materialise into three main challenges in marine sciences:

3.1. Observing and understanding the ocean through Big-Data and AI

Remote or *in-situ* ocean observation instruments producing Big Data that is subsequently analysed using AI will likely open a new era in ocean data collection and analysis, contributing substantially to increase our understanding of the ocean at small or large spatiotemporal scales. Some research fields are already transiting through this paradigm change, as is the case of satellite remote sensing. When exploiting remote sensing data, the most usual requirement by end users is to get satellite data interpolated on a high-resolution, gap-free, regular grid. However, the reconstruction of sea surface geophysical fields from partial satellite-derived observations is a challenging, complex task that can be addressed with different strategies. Classical data assimilation is based on simple statistical quantities (e.g. covariance matrix in the case of optimal interpolation) or in the use of an underlying numerical model of the ocean forced with satellite data. Although, the quality, coverage and resolution of ESA's Soil Moisture Ocean Salinity (SMOS)-derived Sea Surface Salinity (SSS) maps and scatterometer-derived stress-equivalent wind products have improved (e.g. Turiel *et al.*, 2008, Fablet *et al.* 2018), new, powerful data assimilations techniques, following the Big Data scheme, have recently emerged, such as the Analog Data assimilation (AnDA) framework, which exploits patch-based analog forecasting operators within a classic Kalman-based data assimilation scheme. AnDa is of particular interest with regards to the upcoming wide-swath surface water and ocean topography (SWOT) mission. Future work will focus on combining these strategies with the AnDA framework in order to develop useful tools to process real observations from the future SWOT altimetry mission. In this respect, the joint assimilation of SWOT observation gradients and nadir along-track Sea Level Anomalies data should be explored as a possible alternative to deal with the correlated noise sources present in SWOT data. AnDa can be applied to any other oceanographic variable, as Sea Surface Temperature or SSS. Multivariate AnDa is very convenient when multiple variables are assimilated at the same time, although some space-reduction techniques should be applied in order to avoid data scarcity. A different avenue for the applications of Big Data to remote sensing is the use of Random Decision Trees to infer so-far unknown dynamic relations between different variables. This kind of approach has been used for instance, to find relationships between SSS anomalies in particular regions and extreme rainfall over land. Random Decision Trees and similar techniques can be used to group and to validate new physical, chemical and biological processes. In this context, DL models and strategies also arise as promising tools to bridge data-driven and learning-based frameworks to model-driven physical paradigms. This may open new research avenues to embed physical knowledge within data-driven schemes as well as to make the most of state-of-the-art model-driven schemes with the additional flexibility and computational efficiency of learning-based frameworks. The latter may be particularly relevant to address model-data and multimodal synergies.

In the Geosciences the use of ML can be classified into four interconnected categories: automation (e.g. labelling data when the task is difficult or time-consuming for humans), inverse/optimization problems, discovery (extract new patterns, structure, and relationships from data) and forecasting. Despite the availability of large datasets from Earth and Ocean observing systems, often extending over long observation times, many of them remain largely unexplored. Wider adoption by the community of open-science principles such as open source code, open data, and open access would allow taking advantage of the rapid developments that are taking place in ML and AI. Creating an inventory of high-quality datasets, preferably covering large spatial and/or temporal spans that have not been studied using ML and that could immediately benefit from using these approaches (low hanging fruit), represents a sensible course of action. In addition, this field needs to foster collaboration of CSIC groups that have a long history of acquiring large Geoscience datasets with the leading groups in AI/ML research to recognize new potential applications. However, we need to overcome several challenges before working with geoscience datasets. The spatiotemporal structure, the multi-dimensionality and heterogeneity of the Big Data in geosciences, data noise, incompleteness and error of the data, as well as emerging datasets such as light detection and ranging (LiDAR) point clouds, are among the most relevant challenges.

Biogeosciences lag behind physical oceanography and marine geosciences regarding massive autonomous observation and data collection. The advent of remote sensing of bio-optical variables (chiefly, chlorophyll *a*) in the late 1970s, and its consolidation as an operational technique during the 1990s, represented a major breakthrough in the understanding of upper ocean biogeochemistry and inaugurated the era of Big Data in marine biogeosciences. A similar revolution has occurred since the last decade in the observation of the ocean interior thanks to biogeochemical (bgc-) Argo floats and other autonomous platforms. Fitted with non-invasive chemical and bio-optical sensors and even video cameras, autonomous drifting robots can take measurements of a wide array of variables (chlorophyll and dissolved organic matter fluorescence, particle backscatter, nitrate, oxygen, pH) all year-round between the surface and at least 1,000 m depth at a frequency between 1 and 10 days during several years. The growing swarm of bgc-Argo floats will soon provide a 4D view of variables characterizing the ocean interior biogeochemistry and microbial biomass in near real-time, and efforts are underway to merge this stream of data with remote sensing observations of the upper ocean (e.g. optical satellites, lidar and radar) as well as other *in situ* and in silico data streams.

AI techniques are poised to play a key role in the merging of multiscale observations of ocean biogeochemistry, providing end-users with high-quality products including uncertainty estimates, and circumventing the high computational needs of ocean biogeochemistry. Reconstruction of 4D biogeochemical fields from relatively sparse observations using AI will surely yield a leap forward in our predictive capacity, overcoming the limitations of classical climatological approaches based on objective interpolation, which neglected key scales of variability in the temporal (e.g., sub-daily, intraseasonal, interannual) and spatial (e.g., mesoscale) domains, and statistical properties arising from highly nonlinear dynamics. Moreover, AI can be used to infer the underlying processes and to discover unexpected causal links, potentially leading to major advances in process-level understanding and prediction of future system states (Reichstein *et al.*, 2019).

Examples of future applications that will benefit from AI and Big Data include: the accurate estimation of carbonate system and nutrients from hydrological parameters; improved estimation of the sea-surface distribution and flux of climate-active gases; the fusion of remote and *in situ* bio-optical data to extend high-resolution surface images of microbial plankton and organic carbon stocks to the ocean interior; and the widespread deployment of imaging devices on autonomous platforms (e.g., gliders and Argo floats) to measure the abundance and taxonomy of microplankton as well as severely undersampled metazoans (large zooplankton and micronekton). Some of the main challenges ahead are (1) sustaining and expanding the array of autonomous ocean observation platforms, (2) designing optimized protocols for quality control and data interoperability, (3) ensuring long-term storage and seamless accessibility, (4) merging heterogeneous data sources in formats that make them readily usable across diverse research fields, and (5) moving from purely statistical prediction to process-based models that embody causal relationships.

3.1. Knowing and protecting marine life via Big-Data and AI

In the ocean, the number of microbial genomes and genes have astronomical proportions. It is estimated that 10^{29} prokaryotes, 10^{26} protists and 10^{30} viruses populate the oceans, which may contain 10^{10} prokaryotic lineages alone. Recent estimates indicate that microbes represent two-thirds of the total biomass of marine organisms (Bar-On & Milo, 2019). Addressing this massive gene and taxonomic diversity is now becoming possible thanks to high-throughput DNA sequencers (HTS) (Logares *et al.* 2012), which generate massive amounts of genomics data (TeraBytes per run per machine). Even though we still know only a small fraction of the total diversity of genes and lineages populating the ocean, HTS increased the amount of available genomic data several orders of magnitude during the last 15 years, and given that the sequencing capacity continues increasing, the amount of available data keeps growing. These data need large computing infrastructures to be stored and analysed, and these requirements will increase substantially in the near future. So far, AI has not been widely used for bioinformatics applied to big genomic data, but it is expected that, in the near future, it will become extensively used for applications such as assembly of short or long reads, finding gene homologies, predicting protein function and finding causative links or correlations between changes in a large suite of biotic and abiotic conditions and organismal abundances.

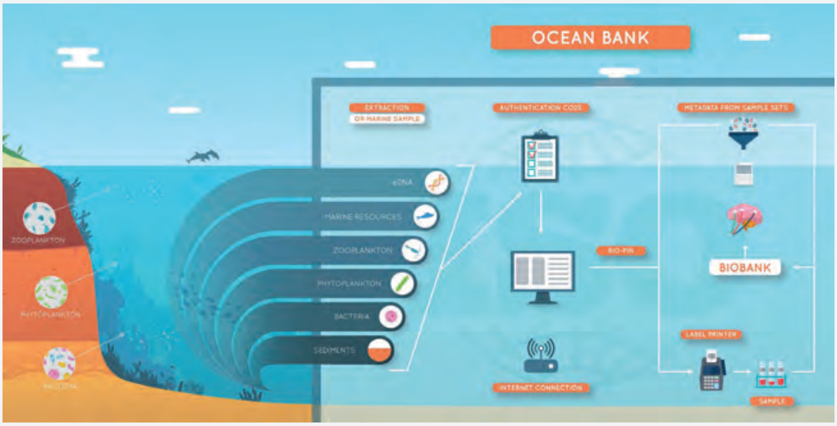
Thus far, DNA (and its actively transcribed gene-coding counterpart, RNA) data have been predominantly used for capturing the genomic information that is present in the ocean in order to understand microbial diversity, species abundance and metabolic activity, ecological interactions, and also how different lineages have evolved. Yet, during the next 10-20 years, HTS techniques, together with all the acquired knowledge on the ocean metagenome will be used for large scale bioprospecting (blue biotechnology), real-time DNA monitoring (to e.g. detect pathogens that spend part of their life cycle in a free-living form, analyse changes in microbial gene expression or track metazoans via eDNA), as well as laboratory-based or ecosystem-level experiments (e.g. mesocosms or *in situ* ocean work). In addition, an important future challenge will be to integrate DNA data from the ocean with other data types from marine observatories to generate a more comprehensive understanding of the ocean ecosystem. For example, chlorophyll observations from satellite data could be coupled to changes in gene transcription detected by gliders or buoys, that also inform on changes in nutrients and currents. In addition, future genomic observatories aiming at capturing DNA from viruses to metazoans may inform of changes in the architecture of ecological networks and link those to e.g. the appearance of a pathogen or other ecosystem-level disruptions. These genomic observatories will become highly relevant in the context of global change (including ocean warming and acidification; see chapter 4), where the distributions of marine species and genes are expected to respond.

To understand microbial life in the ocean, databases represent a key resource. Genomic information is commonly automatically annotated using databases that are: 1) biased towards certain model organisms, 2) incomplete and, 3) too many times wrong. The result is that these automatically annotated genomes that are poorly annotated (because they differ too much from model organisms), present lots of missing data (because the databases are incomplete) or contain errors (because databases contain errors), end up becoming part of these same databases. So far, the best way to generate reliable reference databases is through manual "human" curation. These curated databases can be used to train AI algorithms to perform, at a larger scale, a similar curation task than that initially performed by humans. Such AI-curated databases represent a future challenge that will contribute to understand ocean genomes.

Big Data and AI will not only affect the way we understand microscopic organisms, but also large counterparts. The collection and analysis of machine-sensed (through the use of electronic tracking devices) data regarding animal social behaviour to model behavioural patterns is deeply changing the way to study marine animal populations (Krause *et al.* 2013). Animal-tracking technology allows nowadays gathering exceptionally detailed machine-sensed data on the social dynamics of almost entire populations of individuals living in the oceans. High-resolution aquatic tracking is profoundly revolutionizing our views and understanding of ocean functioning, and now we have a powerful tool for studying the *in situ* behavioural variation in hundreds of free-living individuals, in an unprecedented spatiotemporal scale (Sequeira *et al.* 2018). This will enable the creation of experimental platforms to revisit basic and applied unresolved questions of ecology, coastal management, and conservation biology. For instance, the first reality-mining experiment in marine systems where nearly three hundred fish individuals were simultaneously tracked at a high-resolution scale was developed by a CSIC institute (Laboratory of fish ecology, IMEDEA). This experiment has generated in three weeks approximately millions of 2-dimensional positions and behavioural records at a high temporal resolution (5 seconds in average) and high spatial accuracy (1 m) that have changed our views of ocean functioning and animal social networks with conservation implications. The challenge of the reality-mining approach to aquatic social systems is to close the gap between biological and physical patterns and their underlying processes, providing insight into how animal social systems arise and change dynamically over different timescales.

Big Data and the application of AI have also arrived to the field of ocean conservation (Lamba *et al.* 2019). For instance, the recent footprint of fisheries, when 22 billion automatic identification system messages and the >70,000 tracked industrial fishing vessels were combined with DL algorithms, have created a global footprint of fishing effort. This global fisheries map has revealed that fishing activity occurs in more than 55% of the ocean with serious implications for the conservation of wild fish stocks. At a more local scale, the dynamics of fish length distribution is a key input for understanding the fish population dynamics and taking informed management decisions on exploited stocks. Recent applications of AI to fisheries science are opening a promising opportunity for the massive sampling of fish catches. For instance, a deep convolutional network (Mask R-CNN) for unsupervised (i.e. fully automatic) European hake length estimation from images of fish boxes was successfully developed to automatically collect data from landing (Álvarez-Ellacuría *et al.* 2020). The potential applications of DL in ocean conservation are immense and go beyond the classification of visual, spatial, and acoustic data, with their ability to self-learn patterns in large volumes of data (Christin *et al.* 2019).

FIGURE 8.3–The Ocean Bank can biobankarise any ocean sample (i.e, zooplankton, DNA, sediments or tissue). The biobanking process can be integrated with AI-assisted analyses of Big Data.



This makes deep artificial neural networks very useful for modelling complex ecological systems, real-time monitoring and surveillance sources (Lamba *et al.* 2019).

Understanding the biology of the ocean requires large sampling efforts that may generate hundreds of thousands of samples per year. Oftentimes, these samples become the basis of new Big Data. Organising these Big-Sample sets so that they are properly catalogued and stored, being also available for the community is a challenge. Such organization of samples require combined efforts at the national and international level. For example, the Ocean Bank network initiative (Fig. 8.3) consists of upgrading the concept of sample sharing under a cession-donor scheme. The long-term objective of the Ocean Bank initiative is to create a network of Big Sample banks. Biobank samples may include marine resources and seafood, gene proteins of plankton, chemicals from seabed sediments, marine biomolecules, or seawater. Biobanks will develop to become a safe warehouse for marine ecosystem samples that will be used for improving research on animal and human diseases, marine ecosystem health, food productivity and safety and development of environmental technologies. Traceable Big Sample sets of *biobanks* will open immense opportunities for Big Data and AI. For example, AI-assisted analyses of Big Data may determine the potential value of specific unanalysed samples for different research questions, pointing to samples sets, including samples distributed around the world, that may be the most suitable for addressing a specific question. Implementing biobanks among researchers investigating ocean's life and connecting these large samples sets to the produced Big Data in a context of AI analysis represents a challenge for the next decade.

3.3. Comprehending historical interactions between humans and the ocean

The ocean contains important information that bears witness to continuous human interactions (anthropic action) with the sea. These interactions have been the focus of study for quaternary scientists and social scientists who have collected large bodies of data and developed databases and GIS models. A current challenge is the need to develop complex data models and associated integration, visualization, and analysis tools that manage to integrate the study of the relationships between humankind and the ocean from a holistic and multidisciplinary perspective and not separately as has been the case. In particular, an interdisciplinary problem refers to the lack of a data model oriented to integrate, manage, store and analyse all kinds of structured and unstructured Big Data and associated metadata referring to coastal archaeological remains and underwater cultural heritage (including submerged landscapes and settlements, shipwrecks and downed aircraft), and associated historical and intangible cultural information. Furthermore, there is a need to create new tools for the integration and sharing of historical and archaeological information with data from life sciences.

The creation of new models for integrating data from the human and social sciences to identify maritime cultural heritage should meet the standards of Spatial Data Infrastructures (SDI). The management of maritime historical and archaeological Big Data should also contribute to documentation, surveillance, and data monitoring leading to better governance of this heritage. The use of AI on this data may allow discovering patterns that may lead to new archaeological or historical insights. Particularly, the use of AI in maritime cultural heritage may enhance computer-driven information management. Visualization software and GIS tools, will help formulating formal ontologies that express the nature of reality and the relations among entities, and may help to develop an evolutionary GIS model capable of updating multiple data types, which includes multidisciplinary analysis of life and social sciences.

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CHALLENGE 9

ABSTRACT

The Ocean has shaped human societies, providing resources and ways of communication, trade, exploration and expansion. Understanding the interactions with Society in the past and the present, is essential to tackle the challenges that face the future of the Ocean. With that aim, this chapter develops the consilience between Ocean Science, Social Sciences and Humanities, leading to the integration of diverse methodologies in an interdisciplinary framework. This holistic approach will be used to increase the knowledge and understanding of the interactions of the Oceans with Society by integrating digital and historical data, and natural and cultural heritage management and protection; connecting Ocean and Cultural Heritage Literacy to promote social change and citizen participation in research; developing interdisciplinary knowledge to base Governance and Management and to foster Sustainable Blue Economy, bridging Local and Indigenous Knowledge with Science-based knowledge.

KEYWORDS

maritime cultural heritage

marine governance | ocean literacy

blue economy

local and indigenous knowledge systems

marine protected areas | citizen science

responsible research and innovation

CHALLENGE 9

TOWARDS AN OCEAN-ENGAGED SOCIETY

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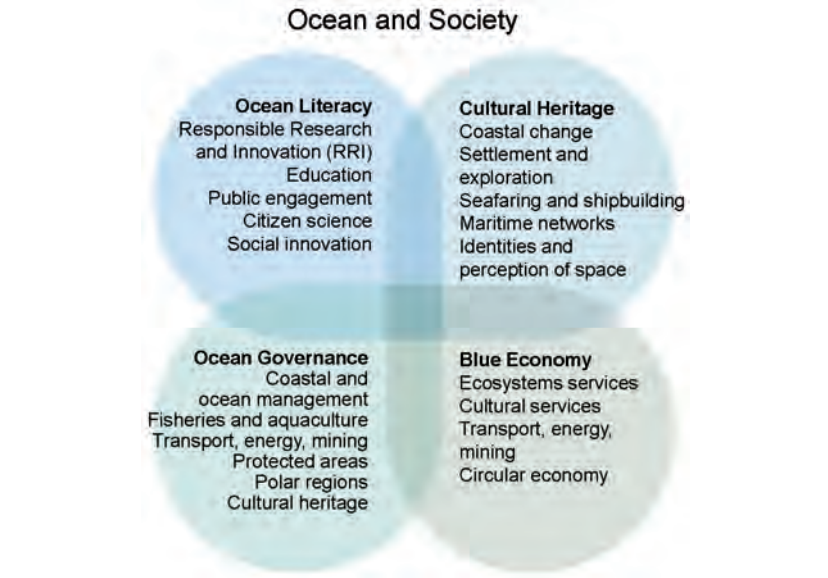
1. INTRODUCTION AND GENERAL DESCRIPTION

Some years ago, Helene Rozwadowski, a renowned historian of the oceans, entitled one of her books *The Sea Knows No Boundaries* (2002). It was a study of the ICES (International Council for the Exploration of the Seas), probably the first organization to identify the oceans as a transdisciplinary and collaborative research object.

The sea knows no boundaries indeed, though it is a boundary object and it has some limits, since marine resources and biodiversity are today seriously threatened. Our blue planet is at risk. Throughout history, the sea has been many things and has played many different roles. Historically, the seas have located empires and business, networks of humans and commodities. Over the waters, chartered companies, spices or oil routes were established. The

FIGURE 9.1–Ocean and Society



oceans have witnessed hundreds of conflicts, naval battles, and piratical encounters, but now it is time to rescue the ocean's role as a common theatre and as a boundary object for international cooperation, for if the sea knows no boundaries, nor should oceanographic studies, maritime courses, hydrographic and bathymetric charts. Over the centuries, the oceans have been the school for collective endeavours for fishing, studying the fauna, transporting natural species, measuring the world or making astronomical observations. Furthermore, Spain has an historical background and a cultural heritage fully linked to the oceans, navigation and life on board. Numerous naturalists, sailors, astronomers, biologists, and oceanographers have participated in joint nautical undertakings. They have lived and worked on board of their floating laboratories, travelling academies, corvettes, frigates or oceanographic vessels. The sea knows no boundaries. It encircles and encompasses the world, as the Shield of Achilles reflected, as the first circumnavigation we are celebrating today demonstrated. All the oceans were connected. Common matters of different disciplines, collective concerns for humankind float on, navigate through and dive into the oceans. We may survey over its horizon, very likely, the future of our planet Earth.

Keeping in mind this historical background, this challenge aims to develop consilience between Ocean Science, Social Sciences and Humanities, leading to the integration of diverse methodologies in an interdisciplinary framework. This holistic approach will be used to increase the knowledge and understanding on the interactions of the Oceans with Society in four main areas: Maritime Cultural Heritage, Ocean Literacy, Governance and Blue Economy, the four of them interconnected in a quadruple helix model as described in Fig. 9.1.

1.1. Maritime cultural heritage

Maritime Cultural Heritage (MCH) includes material and immaterial cultural heritage in water and its terrestrial surroundings. Broadly speaking is an interdisciplinary domain that encompasses anthropology, archaeology, history, architecture, art science or literature. MCH refers to studies of submerged landscape and archaeological sites, cultural resources, historic waterfront structures, maritime traditions and lifeways of the past and present (Claesson, 2011). For each historical period, MCH considers aspects related to the expansion and interconnectivity of human networks, the integration and development of human societies, the impact related to navigation, the economy (development of maritime trade) and technology (with special focus in the study of shipwrecks and underwater landscapes from Palaeolithic to XXI century). It focuses into the History and Culture of People that have lived and used the oceans for thousands of years.

It is worth mentioning that tangible and intangible MCH are sometimes two sides of the same story. On one side, significant or prominent coastal places, seashores and the open sea have been transformed and visited by humans. On the other side, maritime and coastal processes (e.g. Holocene sea level-rise, environmental change and coastal erosion) may have also changed the physical and landscape characteristics of those places. Owing to these material imprints and changes, legends, tales or myths have developed on such places. One key element of MCH is the relation between cities, urban networks and cultural landscapes with the past, and projections of "imagined community". Literary and historical, oral and written traditions operate in a framework that is usually in need of permanent revision. Education and research can be a useful tool to understand not only the past but also the present and future perspectives, or to propose new strategies of understanding and communication. Beyond this simple idea, a discourse can be elaborated on the importance of the MCH component as an identity and memory factor in human history. The ocean is also a network of knowledge (e.g. due to exploration and seafaring) and a recurring theme in Literature and Art. The ocean is an agent of creation and wealth but also of destruction (due to natural phenomena as hurricanes, tsunamis, etc.). As such it has been part of the popular imagination of the peoples, especially in coastal areas, and not only intertidal, threatened by natural hazards, important in the life and survival of communities through the centuries (Mack, 2011).

1.2. Ocean Literacy

The paradigm in which research and development (R&D) is produced, managed and legislated is changing. The public is moving from being a mere spectator to becoming a necessary pillar for the scientific production process to be meaningful and responsible. This process is part of the so-called Responsible Research and Innovation (RRI), which, based on joint work and shared responsibility of the different stakeholders, aims to align both the process and the results of the R&D, with the values, needs and expectations of society (European Commission, 2014).

From the RRI perspective, there are six dimensions that must be incorporated into R&D practices to achieve sustainable, ethically acceptable and socially desirable results: ethics, governance, open access, gender equality, science education and public engagement. In this scenario and placing itself in the pillar of science education, Ocean Literacy (OL) becomes a key element since its promotion will allow societal actors, as well as the whole society, to have the knowledge and skills required to embrace responsible citizenship and engage in those participatory practices, which will be drivers at the core of initiatives such as UN's Decade for Ocean Sciences 2021-2030.

Ocean Literacy ("OL") is defined as *knowing and understanding the ocean's influence on us, and our influence on the ocean*. An ocean-literate person understands the essential principles and fundamental concepts about the ocean; can communicate about the ocean in a meaningful way; and can make informed and responsible decisions regarding the ocean, its resources and the related hazards (NOAA, 2013). Based on that, a better understanding and a higher engagement are believed to have a positive effect on society's relationship with the oceans, which is also linked with the learning objectives for

Sustainable Development Goals (SDG), in particular to SGD14 Life below Water, and cognitive, socio-emotional and behavioural learning objectives. Increasing the OL of the general public, industry and governance becomes crucial in changing attitudes and fostering a global change towards the reduction of human impact on the marine environment. As proposed by IOC-UNESCO (2017), OL activities will be approached from scientific, historical, geographic, economic, social, gender equality, value, cultural and sustainability perspectives, promoting interdisciplinary thinking and intercultural dialogue. In that sense, the Ocean University Initiative launched in 2019 the GLOSS (GLobal Ocean Social Sciences) initiative to identify central issues and conditions for the involvement of the Social Sciences in the UN Ocean Science Decade (http://ocean-univ.org/gloss/?lang=en).

1.3. Marine Governance

An effective marine governance framework is needed to tackle existing and emerging ocean issues. Marine ecosystems are exposed to the impact of a number of multiple stressors, resulting from many drivers, and in addition acting in different areas. A non-exhaustive list of co-existing pressures includes global change (e.g. warming, oxygen decline and acidification), pollution (litter, NHS), maritime traffic, exploitation of living and non-living resources, oligo/eutrophication and invasive species. A comprehensive assessment of the environmental impacts of those stressors is a prerequisite for a proper integrated management and activity planning of the marine environments, and for the definition of any mitigation and adaptation plans to cope with the impacts on oceans and seas. Over decades, measures have aimed at protecting the marine environment by tackling the impact of human activities, but maritime affairs have been dealt by separate sectorial policies without fully integrating all relevant sectors (Boyes and Elliot, 2014).

Ocean governance is required to successfully address most of the Challenges identified in the Oceans Chapter. It is necessary for applying the ecosystem approach to fisheries and aquaculture, and to marine management in general (e.g. through application of the Maritime Spatial Planning), addressed in Challenges 3 and 4 while warranting a Healthy Ocean (Challenge 5); to appropriately design monitoring strategies and effectively use the obtained data (Challenges 1 and 8) to, for instance, have a safer ocean (Challenge 5); to cope with climate impacts (Challenge 2) in all marine areas and in particular in polar regions (Challenge 6) and coastal areas (Challenge 7); to engage society and policy makers in the joint task to protect our planet in the benefit of the humanity. Marine Protected Areas are described as the paradigm of marine and maritime governance challenges. Maritime governance also applies to the protection of the underwater and coastal heritage. As scientists we have to promote a partnership with different stakeholders, so we gain knowledge to be better stewards of our ocean planet and how we can use the ocean in a sustainable way. Ocean research needs to move from an area where it detects and repairs to one in which it predicts and prevents, and therefore better understand the ocean. Better models, better observations, observing systems and a thorough understanding of the connections that we have with the ocean so societies can take action.

1.4. Blue Economy

Defining "blue economy", and knowing what exactly means, is not an easy task since there is no international-agreed standard for this concept. According to the EU Blue Economy Report 2019 (European Commission, 2019), "blue economy" refers to all the activities that are based on or related with the marine environment. The World Wide Fund, however, acknowledges that this is a broad definition and that a more restrictive one refers to the use of oceans and its resources for a sustainable and profitable economic development (WWF, 2015). We also find the use of "blue economy" in the context of changing the current economic model based on eco-efficiency and innovations, but related to all the environment and not exclusively to oceans and marine areas (Paulie, 2010). Regardless the specific meaning that one wants to convey when referring to "blue economy", the challenges and problems of the compatibility of human activities and the conservation of ocean and marine-based areas are not new.

We approach the "blue economy" key challenge from the EU perspective introducing marine-based and marine-related activities. Within this general challenge, we intend to address the conditions for this blue economy to be sustainable and compatible with the conservation of environmental assets in marine areas. It is widely accepted that most economic activities will have a significant impact on marine and coastal ecosystems. In a global change context, even activities that are translocated from marine areas can impact them (i.e., acidification of oceans through anthropogenic carbon sequestered from the atmosphere). Although these interactions are usually perceived as destroying or depleting natural resources and environmental functions, they sometimes are meant to improve the biophysical productivity of the ecosystems.

2. IMPACT IN BASIS SCIENCES PANORAMA AND POTENTIAL APPLICATIONS

2.1. Impact

The integration of Ocean Science and Cultural Heritage with the Humanities and Social Sciences will lead to the development of an interdisciplinary framework and the integration of diverse methodologies. This, in turn, will have a significant impact on new knowledge creation through the transfer of results from collaborative multi-disciplinary research and better use of existing data. Integration of scientific data with Local and Indigenous Knowledge Systems (LINKS) will promote a global understanding of the past and present interactions of Society with the Ocean (Trakadas et al., 2020). Multidisciplinarity will encourage better value research for society, fostering citizen co-creation and participation in research programs and projects, and higher social engagement to influence policy-makers and governance, from a local to a global level. It also will develop new policies for economic development and protection, based on new cross-disciplinary and interdisciplinary knowledge-based governance and management of Marine Protected Areas (MPAs), and of natural and cultural heritage, with a stronger engagement, influence and impact on stakeholders.

2.2. Potential applications

- Integrated study of a territory (e.g. islands, coastal areas), landscapes or seascapes, with the incorporation of LINK to of science-based knowledge.
- A holistic approach to Ocean Literacy, connecting Marine Sciences with Humanities and Social Sciences to better promote and assess behavioural changes and engagement.
- An integrated and governance, management and planning of protected areas (e.g. with natural and cultural heritage), or fisheries and aquaculture, connected with LINKS, developed geographically or interdisciplinary (e.g. World Heritage UNESCO).
- Integrated economy development planning by connecting ecological services with cultural services and sustainability in the long term.

3. KEY CHALLENGING POINTS

The overall challenge is to develop consilience between Ocean Science and Social Sciences and Humanities, leading to the integration of diverse methodologies in an interdisciplinary framework. Five scientific key challenging points have been identified for addressing relevant social, cultural, economic and governance challenges.

3.1. Breaking barriers, integrating Ocean Science and Cultural Heritage with the Humanities and Social Sciences

Humanistic disciplines have developed lines of research and methodologies to study the traces that humans have left at sea and in its depths. Integrating an Ocean and Society vision is based on the fact that the ocean has three components: the first is the water, its physical environment; the second one is the living organisms it contains; and the third is the cultural heritage that humans have left over the centuries. These three components are generally treated separately. Leaving any of them aside may lead "Ocean Science" to a conceptual error, preventing a global understanding

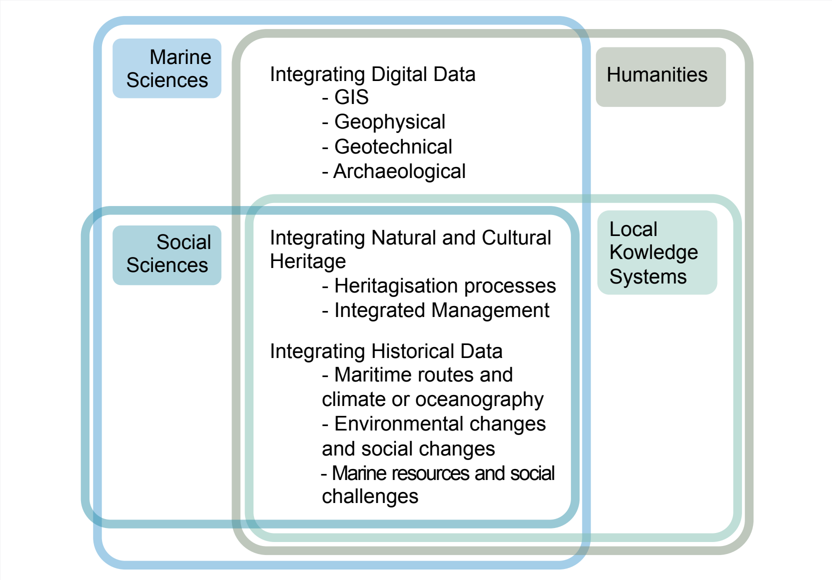
Our challenge is to define and follow a path of consilience between Ocean Science and the Humanities and Social Sciences. Since its origins, the ocean has marked the development of a cognitive geography, as technology and navigation have mapped and created the cartography of the planet Earth. Humans, despite their terrestrial connection, have a maritime vision of the world. However, MCH and marine sciences have typically been disconnected. International law (as the UNESCO Convention 2001) provides a solid basis for a more cooperative and connected approach, being promoted in recent times, as reflected in the development of The Ocean Decade Heritage Network: Integrating Cultural Heritage Within the UN Decade of Ocean Science 2021-2030 (www.oceandecadeheritage.org).

Multidisciplinary integration should be done around the following methodological and data sharing aspects, showed in Fig. 9.2:

Integrating Digital Data:

History and archaeology can generate vast quantities of, increasingly, digital data that reflects the evolutionary relationship of humans with the ocean. These data often have a spatial component and overlap with spatial data collected by and for other disciplines especially within the sphere of ocean science. For example, remote-sensing technologies developed for seabed

FIGURE 9.2—Integrating Ocean Science and Cultural Heritage with the Humanities and Sciences.



characterisation and exploitation have been developed for prospection and monitoring of underwater cultural heritage. These technologies produce large data volumes, comparable with the point clouds produced by terrestrial laser scanning and LIDAR. There is a need for common data standards in spatial data infrastructures (SDI) and Geographic Information Systems (GIS) to promote collaboration and multi-disciplinarity between the humanities and sciences. Digital data also needs to encompass the multi-scalar (full-ocean scale to wreck site specific) and time transgressive (changes during and an individual tidal cycle to hundred thousand-year sea-level cycles) nature of ocean human interactions (in collaboration with challenge 8 Oceans of Big Data and Artificial Intelligence).

Integrating Historical Data in Marine Sciences

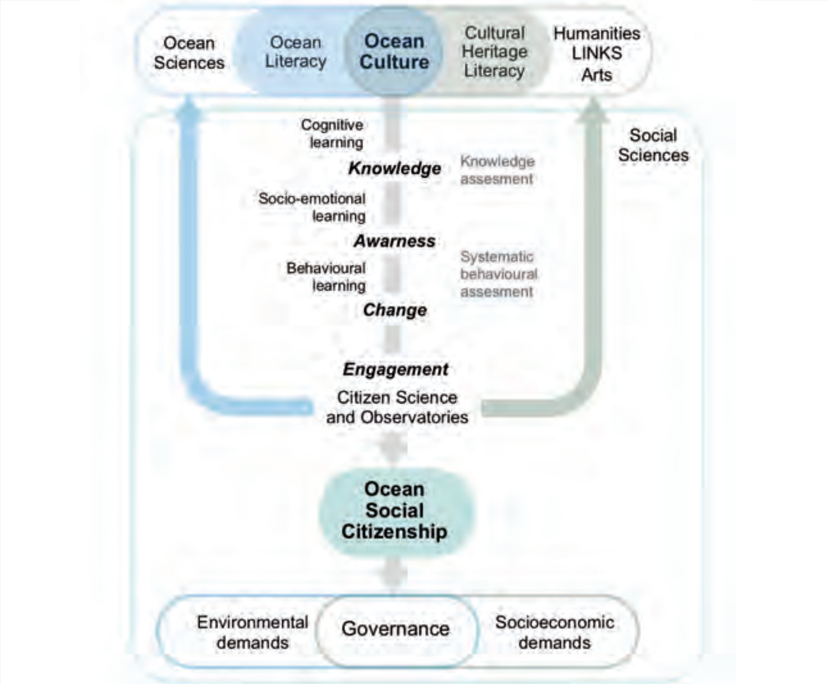
Relevant historical and archaeological information to be integrated will be data regarding seafaring, opening of sea routes (trade winds, trade networks), human migrations and settlements but also travelling narratives and cartography, identities and perception of space. Maritime routes are a function of obligatory points of passage, which are strategic places, of physical constraints (coasts, winds, marine currents, depth, reefs, ice) and of political borders. Natural phenomena, as hurricanes or tsunamis, have also conditioned world navigation disrupting logistics, strategies and posing new challenges in spatial economy throughout history (Schwartz, 2015; https://webs.ucm.es/info/cliwoc/). Environmental, climatic changes and pandemic impacts had also impact on maritime life, affecting demography, social organization of maritime settlements, technology practices and specialization of maritime industries. Historical and archaeological information on past human coastal communities are essential resources in understanding the foundations of present human population concentrations in maritime locations vulnerable to such environmental change, and may provide useful information for predicting future trends.

Integrating Natural and Cultural Heritage Management and Protection
The coasts and the sea are home to rich and vulnerable environments, animal and vegetal species. MCH can then be spatially linked to natural protected and natural vulnerable areas. When considering Heritage as a whole, there is often a natural vs. a cultural dichotomy in historiography and research. But is this dichotomy real? Integrated Coastal Zone Management policies and climate change directives (e.g. from the IPCC panel) tend to underestimate the role cultural heritage approaches can play in the debate about coastal and oceanic management in the frame of current climate change. In this sense, MCH is an example of the potential a joint cultural and natural perspective might have in these issues.

3.2. Connecting Ocean Literacy and Cultural Heritage Literacy to promote behavioural and social change as well as citizen participation in research

The way society changes its behaviour, interests, attitudes, understanding and interactions towards the ocean due to fostering OL, remains mostly unexplored. Monitoring those aspects would require formal long-term evaluations of the outreach, public engagement and other types of science communication initiatives, combined with large-scale Social Science studies, at different societal levels. As stated by Asheley et al (2019, and authors cited), raising awareness alone does not necessarily assess if a change in attitude and behaviour has been adopted, and understanding the influences of human thought and behaviour is just as important. Therefore, a key point is to incorporate the assessment of OL interventions with existing structured, systematic

FIGURE 9.3–Integrating Ocean Literacy and Culture Heritage Literacy



approaches, using empirical methods to collect data and behavioural research techniques that explain perceptions and understanding of human behaviours and their underlying mechanisms (Ashley et al. 2019).

Another key point, connected to the previous one, is to address OL in an interdisciplinary approach connecting it with Maritime (Ocean) Cultural Heritage Literacy, that could be defined as *knowing and understanding how the interaction with the oceans has shaped human societies, globally and locally*. From this perspective, information about cultural heritage is fascinating for the public and allows citizen participation in many OL topics. Information on cultural heritage is also essential to understand the past, present and future of humankind's relationship with the seas and oceans, as well as the relationship between the ocean and human societies in its historical and anthropological dimensions.

This interdisciplinary approach, favoring the implementation of the social and human dimension to OL ("e.g. integrating history, Local and Indigenous Knowledge Systems –LINKS, or arts"), towards a holistic Ocean Culture (Fig. 9.3), will foster knowledge transfer and public engagement, will improve governance and will have societal benefits. The implementation process will need the participation of a wide range of experts, including scientists from different ocean-related disciplines, but also human and social researchers (archaeologists, historians, sociologists, anthropologists, psychologists, geographers, economists, etc.), communication professionals (science journalists, heads of public outreach, science communicators, graphic designers, media professionals, etc.), or artists (visual artists, writers, performing artists, etc.), developing complementary ways to improve knowledge and understanding. It should be adapted and developed to make it relevant locally, with a strong involvement of society, including the participation of a broad range of stakeholders, local communities or social organizations, in co-creation processes and citizen science initiatives. As stated by IOC-UNESCO, Ocean Literacy OL should be understood as the development of a civic relationship with the ocean. The final aim would be to build an Ocean Citizenship, but with a strong social orientation, being able to hold values, understanding and attitudes shaping not only individuals but also collective mutual relationships with the ocean and so, influencing policy-makers and governance, from a local to a global level.

The approach includes also the challenge to change the citizen science positioning within the scientific community, both in Marine Sciences and in Humanities. Some scientists still have doubts on how to integrate citizen science in their research, and are skeptical about the quality and potential of the data collected by volunteers. CSIC strategies should include specific actions to demonstrate the validity of citizen science data through its integrated data system by: a) highlighting the potential to provide reliable and useful data to help approaching real-life problems such as those related to ocean health, exploitation and natural or cultural heritage conservation; b) demonstrating that the methodology can be used in a number of scientific research-projects, and not just for activist movements; and c) disseminating the project results in a way that policy-makers can understand their value so that they can engage in providing funding and long-term support.

3.3. Interdisciplinary knowledge-based Governance and Management of MPAs

The conservation of the marine environment has historically lagged behind the conservation of terrestrial ecosystems. Greater technical challenges to access marine habitats and higher associated costs make it difficult to study the former. Still, both the number and extension of marine protected areas are rapidly increasing. In 2020, a total of 16,924 marine protected areas (MPAs) are documented around the world, covering nearly 27 million square kilometers, equivalent to 7.43% of the seas and oceans' surface and 17% of the coastal waters (Protected Planet 2020). Despite the recent increase in the MPAs, additional efforts are required to fulfil the international commitment acquired by the signatory parties of the Convention on Biological Diversity (CBD 2017) to protect 10% of marine ecosystems. It is essential to declare new protected areas among those with significant value for biodiversity and ecosystem services.

In Europe, the Natura 2000 Network is the most ambitious biodiversity conservation initiative worldwide. By the end of 2018, this network included more than 3,150 marine sites covering over 550,000 km^2, almost 10% of the total EU marine surface.

While still under development, in Spain the only consolidated network of MPAs (with homogeneous protection and management regulations) is the network of Fishing Reserves (FRs). These are not strictly speaking protected areas, since these spaces are declared with the purpose of protecting and promoting fisheries resources in adjacent waters. Currently, the Spanish FRs network includes ten reserves managed by the national Government and another ten managed by regional governments.

Other networks of MPAs are still defining regulatory or managing frameworks. Within Natura 2000, the network of Special Protection Areas (SPAs) for Seabirds is the one in a more advanced implementation stage. It consists of 39 spaces that were legally declared in 2014, but it is not yet actively managed. To date, 33 Special Areas of Conservation (SACs) have also been declared in the four marine demarcations: Canary, North Atlantic, Strait and Alboran, and Levantine-Balearic. Additionally, the LIFE + INDEMARES project identified 10 areas in Territorial waters with habitats and/or species included in Annexes I and II of the Habitats Directive.

One of the main problems is that the legal declaration of protected areas entails the prohibition or limitation of human uses, in order to preserve natural values, which is beneficial for biodiversity and certain socioeconomic sectors, but detrimental for others, so that conflicts of interest arise between different social groups. Therefore, it is necessary to study the protective role of legislation and management.

To fulfill the goals of MPAs, the following research questions need to be addressed: Are the FRs and MPAs effective to protect biodiversity after their declaration? Are there significant differences between MPAs with active management and those not managed or that, until now, have only passive management mechanisms? Are there significant differences between MPAs and adjacent unprotected areas? Are MPAs environmentally and economically sustainable? Do stakeholders perceive the effects of MPAs in a similar way or do they differ substantially?

The answers to these questions should be approached by a cross-disciplinary implementation involving ecologists, marine biologists, geographers, economists, and sociologists, among other specialists. Together with citizen participation, in the form of participatory territorial planning and citizen science, we team up to evaluate the environmental, social and economic sustainability of MPAs.

3.4. Towards a sustainable blue economy?

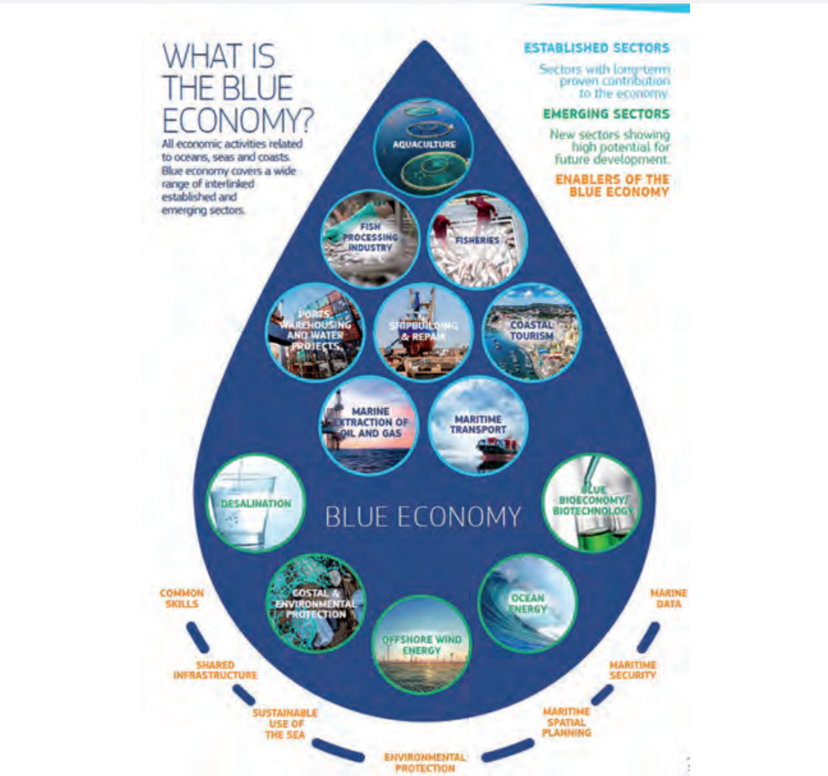
In the European context, several directives, such as the Red Natura 2000, and demonstrative programs, such as Interreg and LIFE +, address the conservation of marine and coastal habitats. At the same time, many regional governments promote the declaration of marine and coastal protected areas although, paradoxically, they also facilitate their destruction and change by fostering urban development and equipment demanded by the tourism industry. This illustrates the latent tension between the conservation of marine areas and the generation of incomes from marine-based activities. From a "blue economy" perspective (Fig. 9.4), the fundamental challenge faced by the marine scientific community lays on the need to provide standardized economic statistics that support efficient environmental and economic policies and that reflect the real contribution of marine natural areas to the economy, considering both the positive and negative impacts of human actions. Statistics and information gathering protocols must be developed considering the current debate about the implementation of an ecosystem accounting system satellite to the current System of National Accounts (United Nations et al., 2014). The gap between current statistics in national accounting and future ecosystem accounting systems lay in two main challenges.

On one hand, when it comes to measure the ecosystem contribution to national income, current statistics omit how the changes in the stock of natural capital affect the change in the value of the environmental assets that, ultimately, reflect the value of future consumption and therefore the capacity of the ecosystem to continue providing the same production in the long-term (Campos et al., 2019). In other words, national accounts only consider the production during the given period, and not the changes in the ecosystem asset that would condition the production in the long-term. Without this information, we cannot know whether current levels of production are sustainable, connecting with the concept of sustainable income.

On the other hand, there is a need to estimate the direct contribution of the marine ecosystems to the production of cultural and ecosystem services that are not explicitly incorporated in official statistics and economic accounting systems. Although this only relates with human consumption, and not directly to the idea of sustainability of the ecosystem, it is indeed an important dimension to understand how humans benefit from ecosystems and how this should be considered in decision-making. Special attention must be given to non-market ecosystem and cultural services, which fall in the category of public goods, with the usual problems associated with their economic valuation.

There are also important impacts from natural, oceanographic and geological processes that need to be considered as they may end in destructive events, with great impact to our society. We face here the role of "critical facilities", which include human-made structures that because of their function, size, service or uniqueness will have the potential to cause serious damage or disruption in vital socio-economic activities. A main goal related to "blue economy" should be to develop proper plans and measures to protect these facilities from hazardous natural phenomena. Some examples are the geological submarine processes (e.g. earthquakes, landslides, tsunamis), considered as serious threats and constraints for these key infrastructures (i.e. nuclear power-plants near the coast, gas reservoirs and submarine cables). Strategies for critical facilities include relocation, strengthening, retrofitting and revising operations, adopt emergency preparedness, response and recovery programs. Another aspect related to this challenge is the "induced seismicity", which refers to moderate-magnitude earthquakes caused by human activity that alters the stresses and strains on the Earth's crust. Induced seismicity can also be generated by the injection of carbon dioxide as the step of carbon capture and storage, which aims to sequester carbon

FIGURE 9.4– Blue Economy diagram. Source: European Commission (2018: 5).



dioxide captured from fossil fuel production or other sources on Earth, as a mean of climate change mitigation.

All these aspects should be taken into account to understand from an economic point of view how human activities interact with marine and coastal ecosystems and natural habitats and require an important interdisciplinary effort between scientific disciplines. Oceanography, marine geosciences and marine ecology should provide the bio-geo-physical base needed to build the economic models that predict how the variations of environmental assets occur at given environmental conditions and interaction between production and capital. It is also important the involvement of the different stakeholders in the marine and coastal areas to understand the role of different ecosystem and cultural service and, ultimately, the incomes they provide to society. All this represent, very broadly, the main challenges associated with a society that seeks a "Blue economy" and, at the same time, avoids the temptation of following this path without sound scientific information for making this "Blue economy" sustainable in the long-term.

3.5. Oceans as networks of knowledge, bridging local and science-based knowledge

The science-based approach generates an essential type of knowledge upon which a highly significant part of human history has been built. However, a holistic approach to the Ocean needs to take into consideration other types of knowledge that are not necessarily based on the same principles and methods. Local tradition, community knowledge and self-experience also provide meaningful and useful information and ideas that help to build a diverse, multi-vocal, approach to address the challenges currently faced by human societies.

In this context, this challenge aims at contributing to bridge the science-based knowledge and the local, indigenous (LINKS), or citizen-based experiences and roles in relation with oceans and maritime cultural heritage. Efforts have been made in the last decades to reduce the gap between these different types of knowledge by, for instance, improving the way researchers disseminate their scientific results or by initiatives to integrate local communities into the heritage research and heritage preservation processes (e.g. data compiling, monitoring, decision-making), but such efforts are still limited. We propose to develop the following approaches to bridge these diverse types of knowledge:

Addressing heritagisation processes in Oceanic Natural and Cultural Heritage:

The process by which specific groups give a social value to objects, places or practices that represent their history, tradition or way of life has become known as heritagisation. This process has a subjective component, as different individuals, communities or stakeholders may have different visions and perceptions of the meaning of heritage and how it should be preserved and managed.

Concerning to research on heritagisation processes, oceanic natural and cultural heritage still occupy a marginal position. This is a field that needs further development. As it is discussed in KPC1, to address this there is a need for a more comprehensive and effective integration of maritime natural and cultural heritage. An integrated approach to marine spatial planning (ICZM, or "Integrated Coastal Zone Management") is a current social challenge, and an objective, which requires conciliation between the varied needs and aspirations of diverse human stakeholders and those of the 'natural' marine environments in which they are situated. Hence, shoreline management, in seeking to protect coastal settlements and their associated cultural heritage must draw on environmental science to forecast probable environmental change and decide where coastal communities will be sustainable in the future.

Managing Threats on Maritime and Coastal Cultural Heritage

As the effects of global warming increase (e.g. sea-level rise, increased frequency of extreme weather events), the concern of different specialists and communities on heritage at risk also increase. As it was the case for the heritagisation process discussed above, these different agents may have different visions on the causes and solutions to the threats to maritime and coastal cultural heritage. In the last few decades, different projects and research teams are implementing solutions for the conservation, protection and governance of coastal and maritime archaeological heritage that include multi-vocal approaches and knowledge. Archaeology is one of the fields that has developed a stronger approach. Citizen participation in appreciation, understanding and protection of coastal and underwater cultural heritage has proved particularly successful with shipwrecks and the study of shipbuilding technology, trade and conflict, demonstrating keen public engagement.

Relevant projects and programmes currently implementing the active participation of local communities for the conservation, protection and management of coastal and maritime cultural heritage exist at European level (Dawson et al. 2017). However, most of these initiatives are limited to the local, regional or national context, the transnational analysis of the situation and the implementation of solutions in areas of international cooperation being extremely rare.

Understanding Local and Indigenous Knowledge Systems and Maritime Communities:

The UNESCO defines local knowledge as the one that "refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings. [..] This knowledge is integral to a cultural complex that also encompasses language, systems of classification, resource use practices, social interactions, ritual and spirituality" (http://www.unesco.org/new/en/natural-sciences/priority-areas/links/related-information/what-is-local-and-indigenous-knowledge/). When referred to maritime communities, local knowledge appears to be highly permeable. Navigation, contact and the exploitation of coastal and marine resources result in an active exchange and sharing of items, beliefs and ideas with other communities. Understanding the development of local knowledge regarding the marine environment and modes of navigation, exploration, migration and coastal settlement can be enhanced through historical study of the evolving cartographies of early portolans, sailing directions, marine charts and maps. Such studies can be multi-scalar both spatially (ranging from the very local to transnational and global) and temporally (ranging from prehistoric iconography to modern pilot books).

Islands and archipelagos can usefully been conceived as laboratories for analysis of trans-oceanic flow of ideas and circulation of knowledge. Hence, specific geographies such as the Antilles can be used to examine broader themes including the impact of imperial expansion (slavery, racism, racialization); international transmission of diseases and epidemics; and transcultural processes which generated local / regional / national identities. With this perspective, it is conceived that knowledge is the result of assembling or combining multiple local know-hows found circulating through groups, objects and texts.

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The ocean is a fundamental element for the Earth and for the wellbeing of human societies. It influences weather and climate, impacting sectors such as marine ecosystems, economy, tourism and human health. Urgent actions are demanded to help in understanding and managing the ocean in a multidisciplinary and integrated way. Here we present the major ocean research challenges for the next decades, CSIC leadership and resources needed.

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