OCEAN SCIENCE CHALLENGES FOR 2030

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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.