The ocean we want: inclusive and transformative ocean science

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Institut de Ciències del Mar, CSIC
Barcelona, 2022

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2021 2030 United Nations Decade of Ocean Science for Sustainable Development

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Institut de Ciències del Mar

EXCELENCIA SEVERO OCHOA

IIP70 Instituto de Investigaciones Pesqueras. Siete décadas de investigaciones marinas

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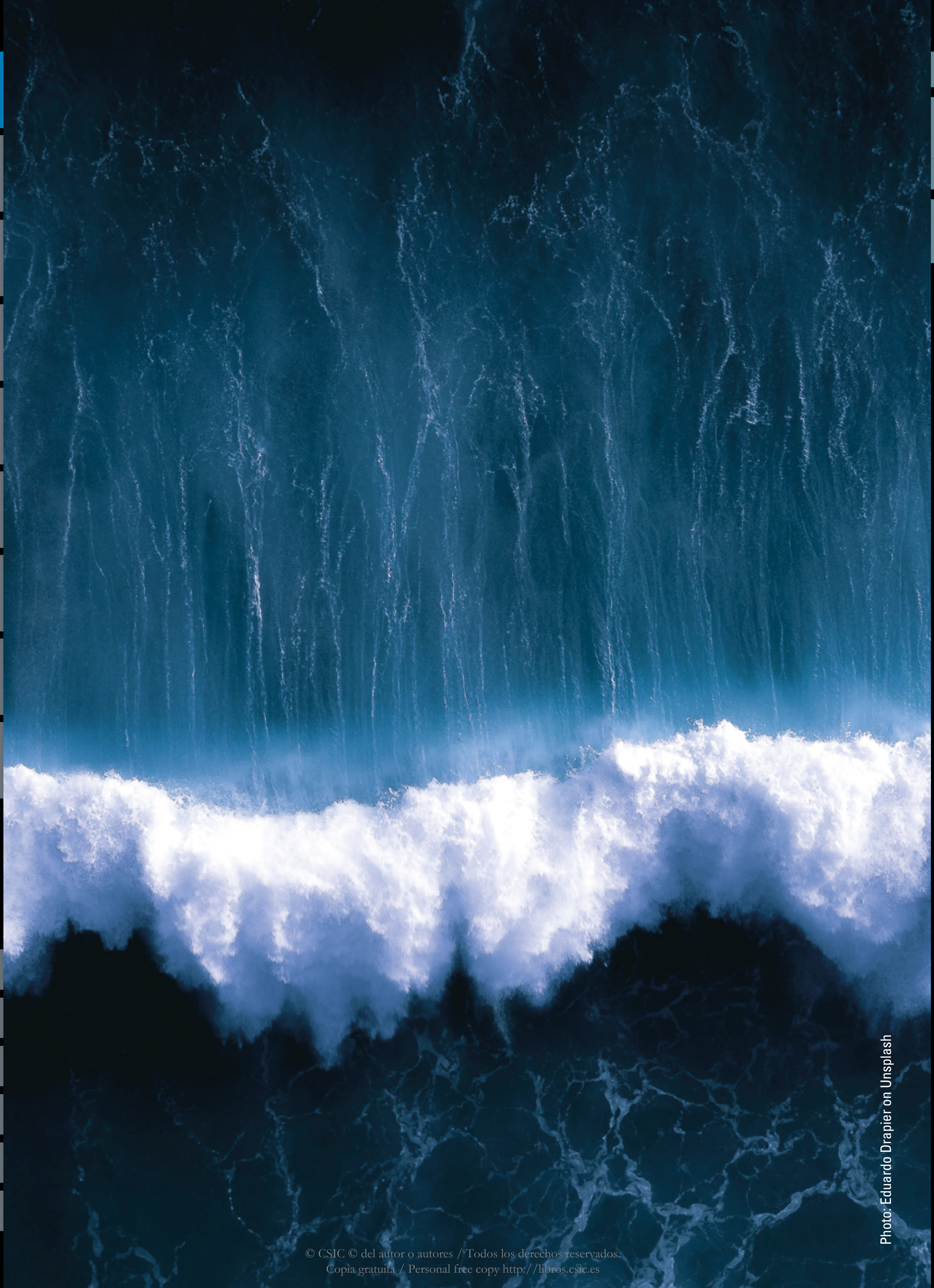

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The ocean we want: inclusive and transformative ocean science.
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The seventy-year history of the Institut de Ciències del Mar and the Unitat de Tecnologia Marina mark the beginning of the Ocean Decade: towards an inclusive and transformative ocean science

Josep L. Pelegrí [(1)], Maria Victoria Martínez de Albéniz [(2)], Josep-Maria Gili [(3)], Jordi Sorribas [(4)]

The Institut de Ciències del Mar (ICM) is one of the leading centres of the Spanish National Research Council (Consejo Superior de Investigaciones Científicas, CSIC), fully dedicated to the interdisciplinary study of the marine environment. Under the motto "Ocean science for a healthy planet", the ICM connects studies of local processes and ecosystems with the complexity and intelligence of our ocean planet, promoting the transfer of science and technology on topics related to the interaction between ocean and climate, conservation and sustainable use of marine ecosystems, and mitigation of the impact of natural and anthropogenic hazards. As a major acknowledgement to its scientific achievements and its commitment to society, the ICM has been recognized as a Severo Ochoa Centre of Excellence, joining some 30 Spanish centres that currently have this accreditation and becoming the first and only marine centre yet to achieve it.

The main objective of the Unitat de Tecnologia Marina (UTM) is to provide services and technical support to the entire Spanish community of marine and polar science and technology. To this end, it is a major actor in the management of two large scientific and technical facilities (ICTS) of the Spanish Ministry of Science and Innovation: –ICTS FLOTA, which coordinates ten oceanographic research vessels, and ICTS BAEs, composed of an international camp and two Antarctic bases. The UTM also has cutting-edge scientific and technological equipment and instrumentation and is a national centre for oceanographic and polar data, forming part of the European infrastructure for marine data and international polar data.

In 2021, the ICM and the UTM are celebrating seventy years of history, with twenty years already in their current headquarters in front of the Somorrostro Beach in Barcelona. The CSIC was created on 24 November 1939, with José Ibáñez as its president and José María Albareda as its ideologue and first general secretary. According to Guerra and Prego (2003), Albareda arranged the creation of the Institut de Biologia Aplicada (IBA) in Barcelona on 10 April 1943. The IBA was attached to the CSIC but based at the Universitat de Barcelona, and its first director was Francisco García del Cid. On 18 February 1949, the IBA created the Marine Biology Section, which in the same year set up laboratories in Blanes, Castelló and Vinaròs.

On 14 January 1949, Buenaventura Andreu wrote a report entitled "Project for the creation of a fisheries research centre dependent on the CSIC". On 3 October 1951, by resolution of the CSIC governing board, this report led to the

The seven great outcomes of the Decade of Ocean Science for Sustainable Development

Outcome 1: A clean ocean, where sources of pollution are identified and reduced or removed. Society generates a wide variety of pollutants and marine litter, such as toxic and persistent organic compounds, heavy metals and plastics. It also causes various physical and biogeochemical alterations of the aquatic environment, from eutrophication caused by excess nutrients to underwater noise of anthropogenic origin. These disturbances come from a wide variety of land and marine pollutant sources, including localized and non-localized sources. Their effects endanger ecosystems, human health and natural resources. It is essential to fill the interdisciplinary knowledge gaps on the causes and sources of pollution and its effects on ecosystems and human health. These insights will underpin the joint formulation of shared solutions to eliminate pollution at source, mitigate harmful activities and contribute to the transition of society towards a circular economy.

Outcome 2: A healthy and resilient ocean, where marine ecosystems are understood, protected, restored and managed. The degradation of marine ecosystems is accelerating due to unsustainable activities carried out on land and at sea. To manage marine and coastal ecosystems sustainably, and to protect or restore them where necessary, we need to improve our understanding of ecosystems and their reactions to multiple stressors. This applies both to the local degradation of the coastal and marine environment and to the global effects of climate change on the marine environment. This knowledge is essential in order to develop tools for implementing actions that create resilience, avoiding situations of no return and thus guaranteeing that ecosystems continue to provide their services for the health and well-being of society and the planet as a whole.

Outcome 3: A productive ocean, supporting sustainable food supply and a sustainable ocean economy. The ocean is a key pillar in global economic development and future human health and well-being, especially in terms of food security and livelihoods for hundreds of millions of the world's poorest people. Knowledge and tools are essential to support the recovery of exploited stocks with sustainable fishing and aquaculture practices while protecting essential biological diversity and ecosystems. The ocean also provides essential goods and services to a wide variety of industries, including the extractive industry, energy, tourism, transportation and pharmaceuticals. Each of these sectors has specific needs in knowledge, technology and innovation, as well as in decision-support instruments that minimize risks and optimize the development of a sustainable ocean economy. Governments also need information and tools to guide the development of sustainable ocean economies and to promote the marine sectors.

Outcome 4: A predictable ocean, where society understands and can respond to changing ocean conditions. The enormous volume of the ocean has not been adequately mapped or observed, nor is it fully understood. It is essential to improve the exploration and understanding of the elements that control changes in the ocean, including its physical, chemical and biological components and their relationships with the atmosphere and cryosphere, particularly in relation to climate change. This knowledge ranges from the shoreline to the high seas and from the surface to the deep ocean, including past, current and future ocean conditions. A comprehensive understanding of the interconnections and responses in ocean ecosystems will support the predictions necessary for a dynamic ocean management that is adapted to changes in the environment and use of the ocean.

Outcome 5: A safe ocean, where life and livelihoods are protected from ocean-related hazards. Hydrometeorological, geophysical and biological hazards, as well as those caused by humans, have devastating, cascading and unsustainable effects on coastal communities, ocean users, ecosystems and economies. The changing frequency and intensity of weather- and climate-related hazards are exacerbating these risks. Mechanisms and processes are necessary to assess priority risks, mitigate, predict and warn of these hazards, and to formulate flexible responses to reduce short- and long-term impacts on land and sea. This means having higher density ocean data and better forecasting systems, including those related to sea level, marine meteorological conditions and climate in near real-time and at the scales of decades. These improvements, accompanied by education, outreach and communication, will allow the formulation of policies and decisions aimed at greater individual and community resilience.

Outcome 6: An accessible ocean, with open and equitable access to data, information and technology and innovation. The data must be managed under the FAIR principles, which ensure that they are Findable, Accessible, Interoperable and Reusable. Educational inequalities in ocean science and knowledge of our environment must be eradicated, and it is therefore essential to ensure access to knowledge, technology and data resulting from experimentation and observation of the ocean, together with precise knowledge of its origins and quality control. This must be accompanied by increased skills and opportunities to collaborate in data collection, knowledge generation and technological development, particularly in less developed countries, landlocked regions and small island states, whose well-being is not unrelated to the global knowledge of our planet. The management, innovation and adoption of sustainable strategies and policies will improve with a greater and better dissemination of oceanic knowledge among the scientific community, governments, educators, companies, the industrial sector and the general public, contributing to the social objectives related to sustainable development.

Outcome 7: An inspiring and engaging ocean, where society understands and values the ocean in relation to human well-being and sustainable development. In order to encourage a change in behaviour and ensure the effectiveness of the solutions formulated within the framework of the Ocean Decade, a profound change in the relationship between society and the ocean is necessary. This can be achieved through approaches based on marine culture, traditional and innovative education and awareness tools, and measures to ensure equitable physical access to the ocean. Together, these approaches will generate a broader societal understanding of the economic, social and cultural values of the ocean and of the multitude of roles they play in advocating for health, well-being and sustainable development. This result will highlight the beauty and inspirational nature of the ocean, thereby influencing the next generation of scientists, policy makers, government officials, administrators and innovators.

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transformation of the Marine Biology Section of the IBA into a new CSIC institute: the Instituto de Investigaciones Pesqueras (IIP). The IIP, whose first director was Francisco García del Cid, had its headquarters in Barcelona, with its initial facilities at the Universitat de Barcelona and laboratories in Blanes (under the direction of Carles Bas), Castelló (under the direction of Buenaventura Andreu) and Vinaròs (which depended on Castelló).

The IIP expanded in September 1952 with the addition of the Vigo centre and in the summer of 1957 with the addition of the Cádiz centre. On 22 June 1963, a new IIP headquarters was inaugurated in a two-storey building with a large aquarium on its ground floor, which was located in the present-day Plaça del Mar, in Barcelona's marine district of Barceloneta.

In 1979, the IIP split into four independent centres: the central headquarters of the institute in Barcelona, which in 1987 was renamed the Institut de Ciències del Mar, the Instituto de Investigacións Mariñas in Vigo, the Institut d 'Aqüicultura Torre de la Sal in Castellón and the Instituto de Ciencias Marinas de Andalucía in Cádiz (Guerra and Prego 2011). In October 1985, the Blanes laboratory became the Centre d'Estudis Avançats de Blanes. In 1992 the Oceanographic Vessel Management Unit was created, and in 2000 it became the UTM.

In 1988 researchers and technicians from the ICM established the first Spanish Antarctic station, which would finally crystallize into the Juan Carlos I Spanish Antarctic Base, run by the UTM since 1999. The UTM is also responsible for managing various oceanographic vessels, including the R/V *García del Cid* (1979), which initially depended on the IIP, and two large oceanographic vessels, the R/V *Hespérides* (1991) and the R/V *Sarmiento de Gamboa* (2008). With the integration of the Instituto Español de Oceanografía as a CSIC centre in 2021, the ships managed by CSIC now make up 90% of the entire Spanish oceanographic fleet.

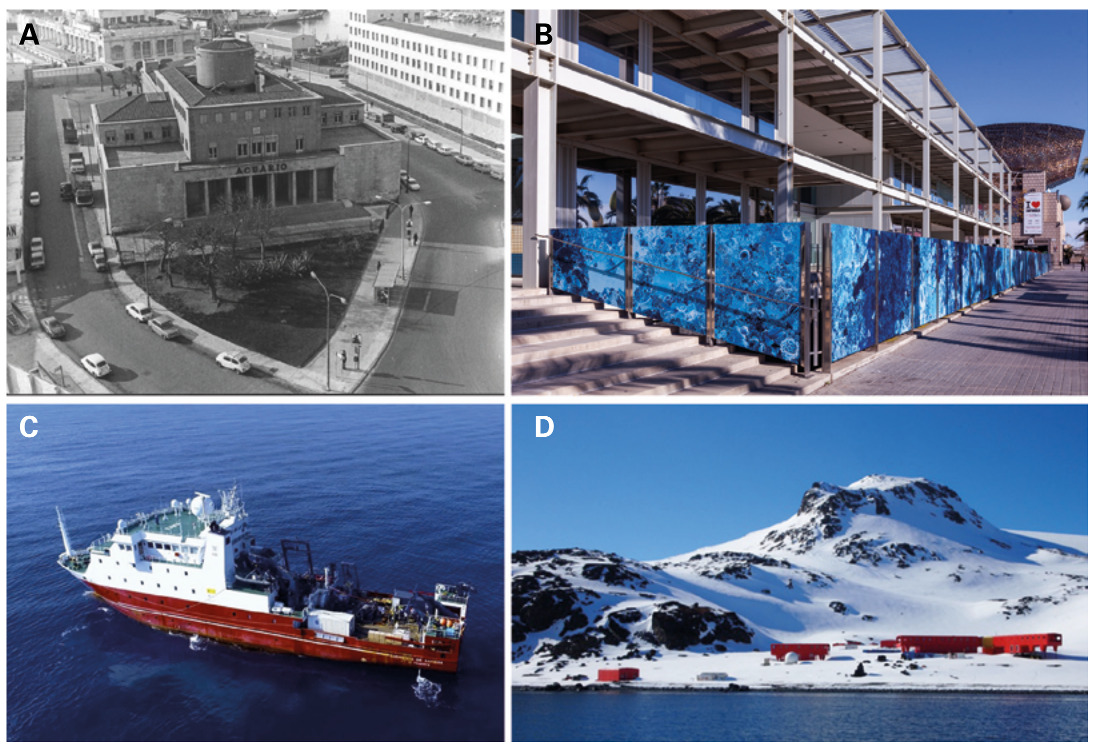

Figure 1. A, former headquarters of the Instituto de Investigaciones Pesqueras in the present-day Plaça del Mar, in the Barceloneta neighbourhood. B, facade of the current headquarters of the ICM, the UTM and CMIMA. C, the R/V *Sarmiento de Gamboa*, one of the ICTS FLOTA vessels. D, panoramic view of the Juan Carlos I Antarctic base.

Directors of the Instituto de Investigaciones Pesqueras, Institut de Ciències del Mar and the Unitat de Tecnologia Marina

Instituto de Investigaciones Pesqueras (1951–1979)

1951–1965 Francisco García del Cid (Bas 2011)
1965–1967 Ramon Margalef (Castellví 2012)
1967–1979 Buenaventura Andreu (Guerra 2012)

Instituto de Investigaciones Pesqueras (Barcelona, 1979–1987) – Institut de Ciències del Mar (1987–present)

1979–1983 Buenaventura Andreu (Guerra 2012)
1983–1987 Carles Bas (Sardà 2012)
1987–1991 Andrés Maldonado (Alonso and Díaz 2012)
1991–1994 Enrique Macpherson (Olivar and Abelló 2013)
1994–1995 Josefina Castellví
1995–1997 Marta Estrada
1997–2001 Rosa Flos
2001–2009 Dolors Blasco
2009–2018 Albert Palanques
2018–present Josep Lluís Pelegrí

Unitat de Tecnologia Marina (2001–present)

2000–2012 Juan José Dañobeitia
2012–2013 Enrique Tortosa
2013–2016 Albert Figueras
2016–present Jordi Sorribas

The ICM and the UTM moved in 2001 to their current headquarters, a 15,000 m^2 building with three floors and a basement located at the end of the Passeig Marítim in the Barceloneta district, and an administrative and logistical structure was created to support the operation of the two institutions: the Centre Mediterrani d'Investigacions Marines i Ambientals (CMIMA). The main nucleus of marine and polar scientific and technical knowledge, not only in Spain but also in the entire Mediterranean, was thus housed on the beachfront near the city centre of Barcelona, with strong roots in its social fabric. The ICM and the UTM focus a large part of their work on sustainable development, and the management and staff of both centres maintain a strong personal commitment to the harmonious integration of society with nature.

Coinciding with the beginning of the Decade of Ocean Science for Sustainable Development (UN 2021), the 70th anniversary of the creation of the IIP is an excellent opportunity to present how the current research of the ICM and the technology and services provided by both the ICM and the UTM are fully focused on the goals of sustainable development. This is why this book, largely written by researchers and technologists linked to the ICM and the UTM, is divided into seven chapters focusing on the seven great outcomes pursued by the Ocean Decade: an ocean that is clean, healthy and resilient, productive, predictable, safe, accessible and inspiring.

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The Institut de Ciències del Mar we want: marine research excellence with social commitment

Valentí Sallarès[(1)], Josep L. Pelegrí[(2)], Josep M. Gasol[(3)], Sònia Sagristà[(4)]

The oceans are essential for life on Earth. They sustain ecosystems, stabilize the climatic system and provide resources that make Earth habitable for humankind. However, human activity is causing rapid global changes that affect the ocean's health and productivity, understood as the resilience to stay within certain boundaries. Global warming, changing weather patterns, sea level rise, ocean acidification and extreme weather events are disrupting the economies of coastal countries and having a profound effect on people's daily lives. Along with the invasion of anthropic structures on the coastline, marine pollution and overfishing, these environmental stressors alter marine populations, harm ecosystems and threaten biodiversity. Moreover, oceans are the sources of devastating natural hazards that hit the coasts episodically, causing huge human and economic losses.

Ocean science for a healthy planet

Facing these global challenges and achieving the sustainable development of humankind will require basic and applied research, resolute action, social commitment and coordinated management. In recent years, the Institut de Ciències del Mar (ICM) has devoted much effort to adapt its vision to this reality and to contribute effectively to reach a sustainable relationship with nature. Under the motto "Ocean science for a healthy planet", the ICM staff have pledged to face these challenges through cutting-edge research and knowledge and technology transfer based on three research challenges: understanding ocean and climate interactions; conservation and sustainable use of marine life and ecosystems; and comprehending and mitigating anthropogenic and natural hazards. These research challenges and a shared vision were identified through a long process of reflection and analysis. The outcome was an institutional roadmap designed to consolidate strengths, minimize weaknesses and capitalize on strategic opportunities through a collective endeavour.

This cooperative work towards developing an organizational structure that is as participatory as possible has brought about a change of paradigm in the ICM's vision, mission and governance. In order to accommodate all views, the classical top-down governance model (staff representatives, tenured researchers and the general assembly) has incorporated several bottom-up committees and working groups engaged in research strategy, core facilities, knowledge transfer and equality (see Garcés *et al.* 2022), and in outreach and communication. In addition, an external social board and a scientific advisory board have also been appointed to provide advice and guide our evolution. As a result of our conviction that we must establish a fluid social dialogue, these changes have led to a new corporate image and enhanced outreach in an effort to get closer to society.

From research excellence to social commitment

The new ICM corporate image is part of an institutional strategy driven by research ex-

Figure 1. Part of the staff of the Institut de Ciències del Mar. Source: ICM-CSIC.

cellence, social commitment and a desire for grassroots linkage in addition to international outreach and recognition. This momentum was supported in 2020 by a major milestone in the ICM's history: its accreditation as a Severo Ochoa Centre of Excellence, which is awarded by the Spanish Ministry of Science and Innovation to Spanish research institutions that are international benchmarks. Of some 30 other centres of all scientific disciplines, the ICM is the first and only marine research centre to attain this distinction. This achievement gave a definitive boost to further advance the transformation of the institute and to consolidate our position as an international benchmark in marine research and a social guarantor of the values of sustainability and planetary awareness.

The Severo Ochoa Centre of Excellence accreditation comes together with one million euros in annual funding until 2023, which has allowed a strategic plan to be implemented with two pillars: reinforcing key operational areas to increase our research impact, and bolstering our scientific strategy. The former was materialized through the creation of the Research Support Office, which functions as a hinge mechanism between the research groups and the administrative staff. It provides support for project management, dissemination and outreach, career development, improving the work environment, talent attraction and knowledge transfer. The institutional scientific strategy pillar has been strengthened through competitive calls that follow the principles of transparency, young talent development, implementation of equality measures and creation of scientific synergies. These calls have allowed us to significantly increase our capacity to attract external talent and retain young talent, reinforce key strategic research lines and improve our core facilities.

In addition to the direct economic benefits and the prestige associated with the Severo Ochoa accreditation, this new work dynamics has strengthened the ICM's institutional representation in various areas of great international importance. Among the most significant achievements is our involvement in the UN Decade of Ocean Science for Sustainable Development (2021–2030), in which the ICM leads and coordinates the Ocean Cities programme, which aims to promote more resilient coastal cities and make the relationship of their citizens with the ocean more sustainable. In addition, the ICM has also submitted its candidacy to become the collaborating centre for the Mediterranean region within the Ocean Decade.

In the local arena, the ICM is closely working with the Barcelona City Council to deploy

Figure 2. View of one of the inner courtyards that hosted activities of the 2021 City and Science Biennial. Source: ICM-CSIC.

initiatives to facilitate the interaction between science and society while raising citizens' awareness of the planetary boundaries, the need for sustainability and the current climate emergency. The Barcelona Mar de Ciència project and our leading role in the 2021 City and Science Biennial are clear examples of this societal commitment.

A shared vision

In addition to these institutional achievements, the ICM has been bolstered through the many scientific individual and collective achievements. These include the coordination of several projects within the Horizon 2020 programme, the attainment of the first European Research Council Advanced Grant, a continued increase in high-impact publications, and many awards and recognitions granted to members of the institution.

The current outlook thus seems quite favourable for the growth of the ICM, but it also entails significant risks in an unstable political context and a complex and changing socioeconomic dynamics. The consolidation of the ICM as a major player on the local and international stage will require it to step up its continual transformation in order to maintain and further improve its training capacity and innovative research excellence and respond effectively to its growing social and environmental commitment. We believe that this dual challenge, which will only be achievable through a collective effort, must guide the ICM's decisions and actions in the near future.

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Photo: Enric Badosa

1. Clean ocean

Andrea G. Bravo, Silvia G. Acinas, Cristina Romera

Seventy percent of the surface of our blue planet is covered by oceans and seas, but since the industrial revolution these waters have become increasingly polluted. Present-day society generates a wide variety of polluting waste from terrestrial and marine sources, including marine litter, hazardous chemicals and heavy metals. Even anthropogenic underwater noise is now considered a type of pollution. Human activities have also caused an increase in the discharge of nutrients into the ocean, leading to eutrophication. This process has severe consequences, such as the excessive proliferation of phytoplankton, which can release toxins and decrease the concentration of dissolved oxygen in the water.

The effects of increasing pollution will be unsustainable for the ocean and will endanger ecosystems, livelihoods and therefore human health globally. It is essential to improve our knowledge of these effects and to consider how pollution sources can be transformed. Research and development of solutions to prevent pollutants from reaching the sea should be mandatory for environmental policy agendas. Among the proposed solutions are the improvement of infrastructure to prevent urban waste from reaching the coast, the chemical neutralization of pollutants before they reach the sea, and the use of microorganisms for bioremediation. These insights will underpin the joint formulation of solutions to eliminate pollution at source, mitigate harmful activities, reduce pollution levels in the ocean and contribute to the transition to a circular economy. Finally, it is essential to make our society aware of the importance of the oceans in human life and of the problems and challenges involved in reducing the strong anthropogenic pressure to which they are exposed.

1.1. Ocean microbes and blue biotechnology

Josep M. Gasol, Ramon Massana, Maria Montserrat Sala, Marta Sebastián, Ramiro Logares, Pablo Sánchez, Silvia G. Acinas

The best known story about biotechnology and biodiversity discovery is probably the one that links the scientists Thomas D. Brock and Kary Mullis to the death row convict Kirk Bloodsworth. Back in the 1960s, Thomas Brock studied hyperthermophiles (prokaryotes that develop at very high temperatures) in Yellowstone. He found a bacterium that grows and divides at temperatures of up to 70°C, and named it *Thermus aquaticus*. He worked for the sake of discovery, to understand the limits of life, and nobody asked him to do applied research. Many years later, Kary Mullis remembered that this prokaryote replicates its DNA at high temperature, and he developed a method for copying and multiplying any DNA molecules using the enzyme isolated from *Thermus*. This technique, named polymerase chain reaction (PCR), has become a buzzword for most of us and led him to win the Nobel Prize for Chemistry and to earn a great deal of money. When PCR was first used in a court case, it demonstrated that Kirk Bloodsworth was not responsible for the murder he had been charged with. Brock never imagined that his basic research could make some people rich, lead to others being acquitted and allow many of us to be tested for COVID19. His work led to significant biotechnological advances and developments.

Many microorganisms, and very diverse

The oceans are teeming with microbes. Up to 10^{29} unicellular prokaryotes and eukaryotes spread over an estimated 10^{11} different species (Locey and Lennon 2016). Thanks to their large metabolic repertoire, which is immensely greater than that of eukaryotes, prokaryotes drive the Earth's biogeochemical cycles (Falkowski *et al.* 2008), to the point that a world with only large multicellular eukaryotes (i.e. plants and animals) would not be self-sustainable. Each prokaryote has 2000 to 7000 genes, and each protist (i.e. unicellular eukaryote) about 30000. While most of the genetic machinery of the microbes deals with essential functions common to most of them (such as DNA duplication and cell division), there are also a large number of "functional genes" encoding for specific functions and metabolisms that drive the biogeochemical cycles. For a given specific function, there are many different gene variants from different microbes –often hundreds of variants in a single location. One can use simple mathematics to figure out the immense diversity of biogeochemical functions that microbes can perform. They can fix nitrogen gas into ammonia, convert ammonia to nitrite and nitrite back to nitrogen gas. They can oxidize reduced iron, reduce oxidized iron (and corrode malfunctioning pipes), can use methane as a source of carbon or produce methane. Microbial metabolisms are extremely versatile, and they can degrade a multitude of substances produced autochthonously in the ocean, in addition to many allochthonous substances that humans have introduced, such as plastics, oil and chemicals of all types. And they probably run many other functions that we do not even know to exist yet. In a recent survey of the global tropical and subtropical deep ocean, we found more than 600000 microbial genes unique to this habitat; of these, 58%

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had not been observed before and 63% had an unknown function (Acinas *et al.* 2021). While some might be related to previously described functions, some may well be unknown yet to science.

Ocean microorganisms and blue economy

It is no wonder that genes present in ocean microbes can substantiate a part of the *blue economy*, that part of a country's economy based on products or services derived from the ocean. The discovery of organisms containing molecules and genes of commercial interest is growing parallel to the exploration of marine biodiversity. By 2025, the global market for marine biotechnology is projected to reach $6.4 billion, spanning a broad range of commercial purposes in the pharmaceutical, biofuel and chemical industries. As of 2017, a total of 12,998 genetic sequences from 862 marine species (Figure 1A) had been patented with international protection filed under the Patent Cooperation Treaty (Figure 1B). Most of the patents are associated with microbial species. They account for more than 73% of all patented sequences in databases (Blasiak *et al.* 2018), though they represent only 19% of named species in the World Register of Marine Species (WoRMS). This underscores the tremendous potential for biological applications of marine microbes.

Biotechnological use of marine microorganisms: a few examples

How can microbial functions be used biotechnologically? Biomass production is one of the key elements. Microalgal biomass has been collected as food and to be used as biofuels since long ago. Polysaccharides (agar and carraginates being the most conspicuous) and other high molecular weight compounds such as alginates are used by the food industry as well as by the cosmetics industry, and the oceanic origin of the microbial active principle is often used to advertise the usefulness of the product. Biosurfactants, bioemulsifiers and exopolysaccharides of microbial origin also have applications in engineering (rock drilling), and bacteria-derived silicas in the form of novel biosilicas with unique electrical, optical and catalytic properties also have great potential in nanomaterials (OECD 2013). Though most currently used antibiotics were isolated from terrestrial sources, it is considered that marine bacteria and fungi are promising bioprospecting sources for new discoveries.

In addition to the application of byproducts of microbial growth, we can highlight the role of microbes in the degradation of substances. Typically, hydrocarbon-eating bacteria such as *Alcanivorax, Cycloclasticus* and *Marinobacter* are used along with surfactants to bioremediate ocean oil spills. Some bacteria have been shown to be able to subsist by just degrading

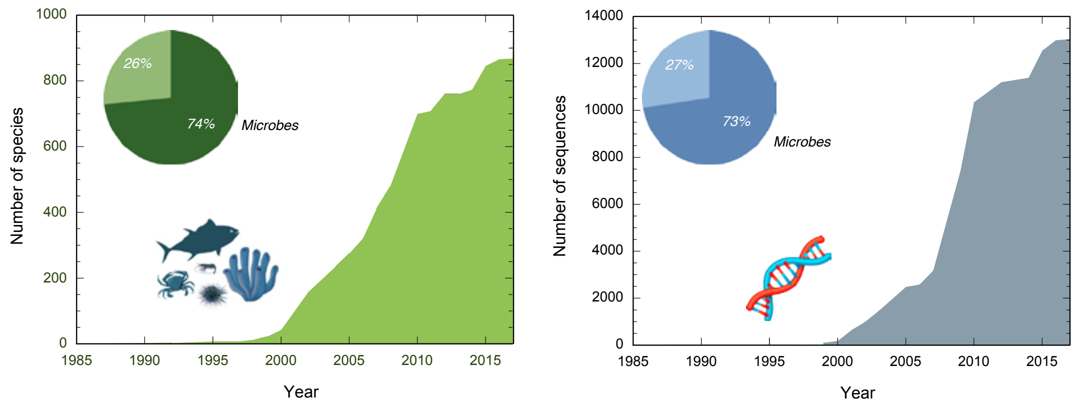

Figure 1. Growing commercial interest in marine genetic resources. Cumulative number over time (1988–2017) of marine species with patented sequences (A) and patented sequences from marine species (B). Inset, the proportions corresponding to microbes. Adapted from Blasiak *et al.* (2018).

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hydrocarbons, and they have been found in all oceans, even at the deepest points of the Mariana Trench, at 11,000 m depth. Inorganic compounds such as methyl-mercury are toxic to most biota, including humans, but not to many microbes. It was already known that methanotrophic bacteria (those that have specialized in degrading one-carbon reduced substrates in the presence of oxygen) are capable of demethylating, and thus detoxifying, this toxic compound, but we have found a large diversity and wide distribution of microbes with such genetic potential in the deep ocean. Efforts are underway to use these marine bacteria in methyl-mercury detoxification and the bioremediation of contaminated marine sediments.

Plastics are emerging as one of the most prevalent pollutants in the ocean, affecting marine organisms of all types. However, plastics are mostly formed by hydrocarbons, and some microbes have developed the capacity to degrade polyethylene terephthalate (PET, one of the main components of plastic). One isolate, *Ideonella sakaiensis*, has even been described to degrade PET and assimilate it as its sole carbon and energy source (Yoshida *et al.* 2016). In a recent study from the Malaspina expedition, we have observed several tens of variants of this enzyme, which is particularly abundant in the deep ocean (Alam *et al.* submitted). These bacteria seem to have evolved and diversified relatively recently, which would indicate that plastic pollution is becoming a source of carbon for deep ocean microbes that help remove the plastic present in the marine environment. Ocean bacteria may be adapting to the pollutants that humans dump into the marine environment.

Another great example of a biotechnological advance based on basic research is the discovery of clustered regularly interspaced short palindromic repeats (CRISPRs). These sequences were unveiled by Mojica and coworkers during the 1990s when they were studying halophilic archaea in solar salterns. Mojica first coined the term CRISPR and proposed that CRISPRs were involved in bacterial immunity against foreign genetic elements (Mojica *et al.* 2005). CRISPR-Cas systems are adaptive immune response systems that protect prokaryotes from bacteriophages and other external agents. The

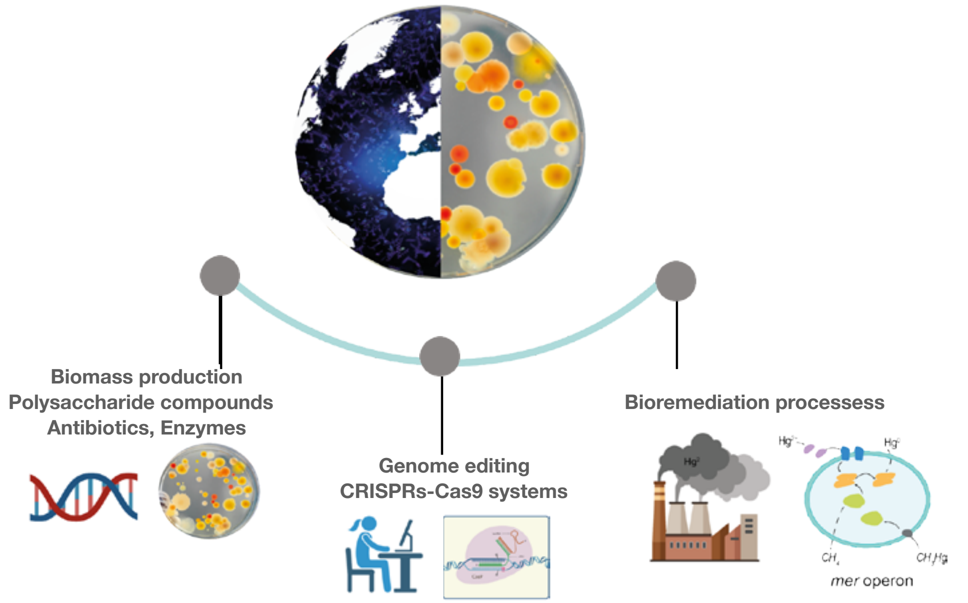

Figure 2. An overview of the presence and importance of microbes in the ocean (upper panel, left), the retrieval of marine biodiversity in pure culture (upper panel, right), and biotechnological applications discussed in the text of the biomass, genetic sequences and genes of these marine microbes.

CRISPR-Cas9 system has been repurposed as a robust genome-editing tool for removing, editing or introducing new genes and regulating gene expression. It is probably the most important scientific discovery of the century and has a tremendous impact on biomedicine and biotechnology. Though Jennifer Doudna and Emmanuelle Charpentier won the Nobel Prize in Chemistry in 2020 for developing the CRISPR genome-editing technology, Mojica's first observations were essential and paved the way for later CRISPR studies. Again, basic research goes first. In a recent survey of the Malaspina expedition, we identified novel CRISPR-Cas system architectures and novel Cas9 variants from the deep ocean that, after validation in model organisms, could be exploited in biological research, biotechnology and clinical applications.

While microbes have much less glamour than other marine organisms such as whales, turtles or parrotfish, they are essential to the functioning of system Earth, and they represent an untapped source of enzymes and compounds that are increasingly populating blue economy initiatives (Figure 2). It is essential that efforts continue to focus on determining microbial and gene diversity, isolating bacteria, archaea, fungi, small protists and viruses, characterizing their genomes and the enzymes and compounds they produce, and exploring their biotechnological potential so that the plethora of useful functions they use to run the ocean's biogeochemistry are also used industrially to improve human lives.

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1.2. The history of trace metal pollution in the sediments of the Catalan Sea

Albert Palanques, Pere Puig, Jorge Guillén

Trace metals are common pollutants resulting from domestic and industrial activities. They are delivered into the sea through rivers, waste effluents and atmospheric emissions. In several countries, the distribution of trace metals in the marine environment is studied systematically and extensively in order to estimate their impact and their economic and social effects, and to take preventive and corrective measures. Many studies have traced and dated the impact of anthropogenic activity on sediments, which record the historical inputs and trends of these pollutants. These studies generally show continuous anthropogenic enrichment of trace metals in coastal areas during the last century due to the increase in industry, urban development, population, agriculture and mining.

In general, the application of environmental regulations, new water treatment plants and other protection measures have helped reduce the discharge of trace metals in coastal areas during the last few decades. However, the effects of these reductions in terms of trace metal concentrations are difficult to identify because it may take several years until they can be recorded in coastal sediment deposits, and also because such records can be affected by disturbing effects such as harbour construction and dredging, trawling, diversion of river mouths and changes in the pollution sources.

Once discharged into the sea, pollutants are affected by several physico-chemical processes and are dispersed by currents and waves. In the Mediterranean Sea, the transport capacity of these processes is lower than in large oceans, so a large part of the particulate pollutant load can quickly settle on the seabed near the coast, thus generating persistent and anomalous concentrations in the bottom coastal sediments. Only extreme hydrodynamic events such as strong wave storms and strong wind-induced currents can significantly resuspend polluted coastal sediment and transport it deeper into the sea.

The Catalan Sea

During the 1980s and 1990s, researchers of the Institut de Ciències del Mar (ICM) studied trace metals in sediments of specific areas of the Catalan Sea, including the Barcelona coast and submarine canyons, the Llobregat river mouth, and the Ebre Delta coast, finding significant trace metal pollution at some sites (Figure 1).

In 2000, ICM researchers participated in a surveillance programme of heavy metal pollution in marine sediments of the Catalan inner shelf led by the Catalan Water Agency (ACA), following the Water Framework Directive (WFD, DIR 2000/60/EC). They established a monitoring network that prioritized the control of sediments in the vicinity of river mouths, where these elements tend to accumulate more. As a continuation of this work, in 2006 the ACA started a second programme to determine the levels of trace metals and organic pollutants in sediments of the Catalan coast, giving priority to the most affected areas of control according to the results of the 2000 project.

These studies identified three sectors: 1) the northern Catalan coast, from the French border to the town of Mataró, where trace metal pollution was very low or null, with only isolated

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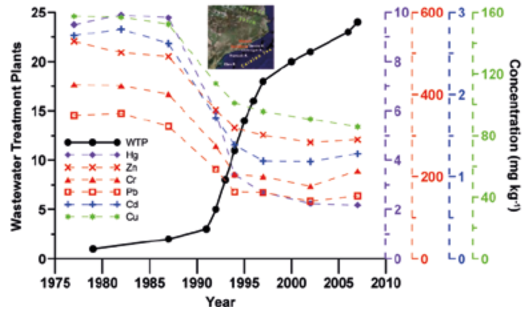

Figure 1. Annual number of wastewater treatment plants working from 1979 to 2010 in the Besòs watershed and record of trace metal concentrations of the sediments on the Barcelona city coast during this period of time. WTP, wastewater treatment plants. Trace metal concentrations correspond with the Y axis of the discontinuous lines of the same colour (from Palanques *et al.* 2017). Map showing the location of the study area

pollution at some points; 2) the Barcelona city coast, which showed very high pollution for most of the studied pollutants, especially Hg and Cd, and 3) the southern Catalan coast, which showed significant pollution decreasing southward, with isolated maximum values of Hg in front of the Francolí river mouth (Palanques *et al.* 2016).

In addition, research studies carried out by ICM scientists from the 1980s to 2010s identified the historical evolution of the trace metal pollution in the most polluted area of the Catalan coast, that of Barcelona city, in front and to the south of the Besòs river mouth. The sediments from this area showed a moderate increase in trace metal pollution during the 1920s and 1930s and a sharp increase from the 1940s to the late 1980s, which was correlated with the industrial development and demographic evolution in Catalonia. From the late 1980s, trace metal pollution levels decreased as a result of the environmental regulations and infrastructure developed in the rivers and on the coast of Catalonia. The highest decrease in trace metal pollution was during the 1990s, when there was the greatest increase in the number of wastewater treatment plants, in addition to environmental restorations and beach nourishments, especially in the Besòs area (Figure 1) (Palanques *et al.* 1998, 2017).

In spite of a drastic reduction of the trace metal pollution, the levels in the Barcelona coast area are still high. In fact, the decreasing pollution trend stopped during the 2000s, indicating a limit of the effectiveness of the applied measures. The Besòs River watershed and the Barcelona metropolitan area are highly populated and industrialized and still produce a significant pollution load. Although this pollution is treated by the waste water treatment plants, during occasional extreme rain and flood events, the capacity of these plants is not sufficient and the excess water is discharged untreated into the sea, forming large plumes of polluted water lasting for several hours (Figure 2). The polluted material is dispersed and settles on the seabed, helping to maintain the still relatively high pollution levels in the sediment (Palanques *et al.* 2017).

In addition, exceptional high-energy storm events can erode part of the highly polluted layer accumulated until the 1980s, causing some increases in the trace metals levels of the surface sediments until it is buried and mixed with less polluted sediments (Palanques *et al.* 2020).

Therefore, although the environmental regulations and plans developed in Catalonia since the 1980s have been highly effective for reducing the trace metal pollution levels, in the most polluted area of this region it is still necessary to develop new strategies and introduce new improvements to reduce the impacts, especially those occurring during extreme rainfall and storm events.

Figure 2. Plumes of turbid and untreated polluted water discharged during extreme rain and flood events on the Barcelona city coast. In yellow, vertical profiles of trace metal concentrations in the sediment showing their historical evolution. (from Palanques *et al.* 2017).

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1.3. Mercury in changing oceans

Andrea G. Bravo, Isabel Sanz-Sáez, Amina T. Schartup

Mercury (Hg) poses a recognized global environmental problem with worrisome environmental and public health impacts (UNEP 2019). While natural sources of Hg such as volcanic eruptions, geothermal activity and weathering of Hg-rich rocks in the earth's crust have always existed, in the last century human activities such as artisanal and small-scale gold mining, coal combustion, production of non-ferrous metals, cement production and disposal of wastes containing Hg have outpaced natural sources. Around 80% of the Hg emitted to the atmosphere from natural and anthropogenic source is deposited in the ocean, resulting in a tripling of Hg concentrations in surface marine waters compared with pre-industrial levels. The World Health Organization has placed Hg among the top 10 chemicals of major public health concern. Spain is one of the 130 signatories of a global treaty, the Minamata Convention, that seeks to protect human health and the environment from the adverse effects of Hg and came into force in August 2017. Some of the convention's proposed actions include a phase-out and phase-down of Hg use in a number of products and industrial processes, a ban on new Hg mines and the phase-out of existing ones, monitoring of Hg air emissions and releases to land and water, and regulation of the informal sector of artisanal and small-scale gold mining. The EU has also established environmental policies for monitoring and modelling global Hg distribution such as the Global Mercury Observation System. Understanding the global Hg biogeochemical cycle of the oceans is key for predicting Hg levels in aquatic food webs and evaluating the impact of reduction strategies on human exposure.

Ocean Hg cycle

In seawater, Hg is present in different chemical forms that are sensitive to environmental and biological conditions. The forms are elemental mercury, Hg^0, divalent inorganic mercury, Hg^{II}, mono- and di-methylmercury, CH_3Hg^+ and $(CH_3)_2Hg$, respectively. Hg^0 is volatile and can be transported long distances in the atmosphere and deposited far away from its source (including the ocean). Also, Hg^0 can be oxidized to Hg^{II} and get into the ocean. In seawater, Hg^{II} can i) be reduced to Hg^0 and re-emitted back to the atmosphere or ii) be biotically methylated into the organic form CH_3Hg^+, and iii) bind to organic matter and inorganic particles and settle to bottom sediment (Figure 1). CH_3Hg^+ formed in aquatic ecosystems can be exported to the sediment, taken up by the food web, biotically or abiotically degraded into inorganic Hg, or methylated to form dimethylmercury, $(CH_3)_2Hg$. Part of $(CH_3)_2Hg$ can be re-emitted to the atmosphere and/or degraded to CH_3Hg^+. Many of these transformations are mediated by the microorganisms carrying the genes *hgcAB* (Hg^{II} methylation), *merA* (Hg^{II} reduction) and *merB* (CH_3Hg^+ demethylation).

CH_3Hg^+ is central in Hg research because it is bioconcentrated and biomagnified in aquatic food webs, reaching 80% to 100% of the total Hg measured in some fish tissue. Considering that more than three billion people rely on seafood for nutrition and that Hg concentrations in fish often exceed environmental quality guidelines even in the absence of local sources, the consumption of Hg-contaminated fish and seafood is the main route of human exposure. Indeed, a recent study performed in 175 coun-

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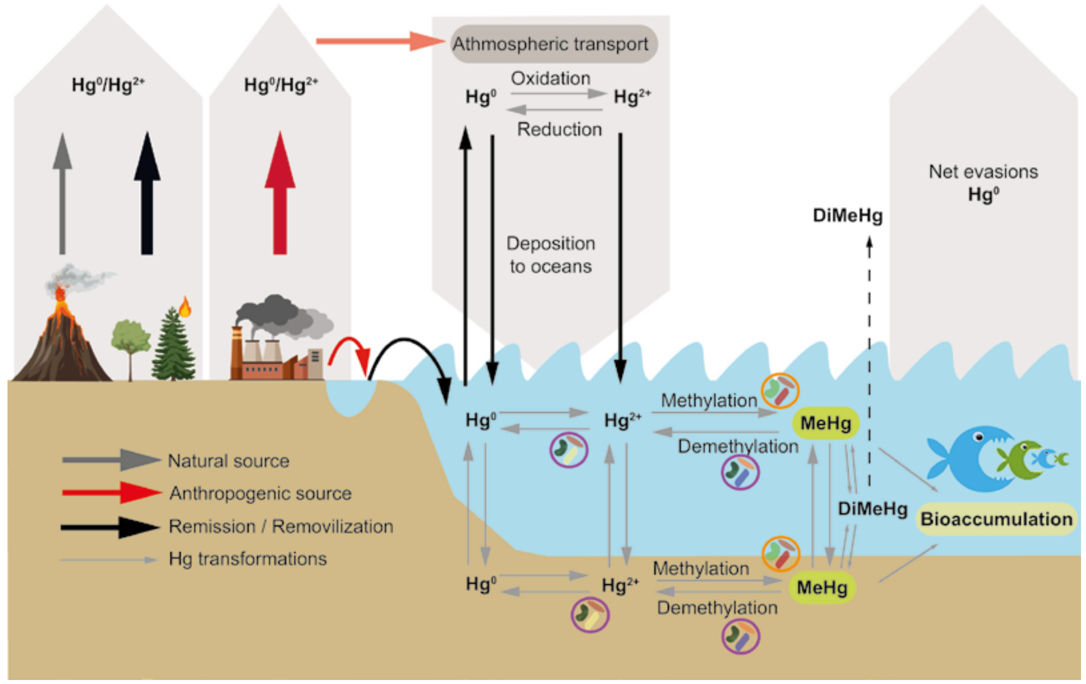

Figure 1. The mercury cycle and the global mercury budgets released into the atmosphere and cycled through the oceans and atmosphere. Mercury transformations indicated focus on those mainly occurring in marine ecosystems, including the water column (blue area) and sediments (brown area). Hg^0, elemental mercury; Hg^{2+}, mercury ion; MeHg, methylmercury.

tries showed that 38% of the studied populations (mainly insular and developing nations) were exposed to levels of CH_3Hg^+ above governmental thresholds (Lavoie *et al.* 2018). CH_3Hg^+ is neurotoxic and can damage the central nervous system, causing tremors, distorted speech, changes in the renal and hepatic function, respiratory failure, dizziness, blurred vision, hallucinations, and even death in severely exposed people.

Despite global efforts to reduce Hg emissions in recent years, the Hg concentrations observed in marine fish from various European seas have not substantially declined (Euro Chlor Risk Assessment for the OSPARCOM Region). Problems added to the Hg levels in oceanic waters are climate change and overfishing. Recently, a model based on 30-year data simulated how environmental factors, including increasing sea temperatures and overfishing, impact levels of Hg in fish, particularly Atlantic cod, spiny dogfish and Atlantic bluefin tuna (Schartup *et al.* 2019). The study concluded that while the regulation of Hg emissions is reducing Hg levels in fish, seawater temperature and prey availability are also important controls on Hg concentrations in pelagic marine predators. For example, overfishing of prey with a low Hg concentration can force some predators to consume Hg-rich prey instead and therefore increase Hg concentrations of top predators. Moreover, increasing seawater temperature can increase the metabolic rate of some fish species, also resulting in a higher Hg accumulation. Another possible impact that should be explored in future research is the role of shifting habitat, as tropical and temperate species move north to cooler temperatures. This poleward movement could result in higher MeHg in biotas because MeHg peaks at shallower depths in the water column in high latitude waters (Zhang *et al.* 2015, Heimbürger *et al.* 2015), which allows phytoplankton to accumulate more CH_3Hg^+. Finally, an increase in temperature may boost the number and volume of the oxygen minimum zones, which are prone to form CH_3Hg^+.

Urgent action is needed to decrease Hg levels in the ocean

In conclusion, global efforts to reduce Hg emissions and releases into our oceans can indeed lead to lower Hg and possibly lower CH_3Hg^+ in seawater (Zhang *et al.* 2016). However, climate-driven changes, such as increasing seawater temperatures, expansion of oxygen minimum zones, water column stratification and changes in food web structures, may offset some of the projected benefits of emission controls (Zhang *et al.* 2021). In addition, delays in policy action (Selin 2018) result in a slower reduction of Hg levels in the environment. We therefore need to act now to curb Hg emissions and releases, and to act more aggressively. Finally, more research is needed to understand how climate change impacts CH_3Hg^+ production in the ocean and biomagnification in marine food webs.

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1.4. Background noise

Cristina Romera-Castillo, Lorenzo Bramanti

The title of the famous documentary "The World of Silence", in which Jacques Cousteau unveiled the secrets of underwater life, was actually not completely accurate. Far from being silent, the underwater world is characterized by a resounding concert: background noise caused by marine animals and geological phenomena, just as in the terrestrial jungle the sounds of animals are mixed with those of the earth and meteorology. However, the equivalent concert that takes place under the sea is not as well known, probably because during underwater diving, the noise of the bubbles produced by breathing deafens most other sounds. Sound is transmitted five times faster in water than in air, so the sounds emitted by some marine animals could travel thousands of kilometres. Moreover, sound is transmited faster in warm than in cold water.

The marine chorus

Most animals emit sounds in the range from less than 20 Hz (infrasounds) to more than 20 kHz (ultrasounds), so they are audible to a wide range of species. Invertebrates, cetaceans, fish and reptiles are able to perceive low-frequency sounds (<5 kHz), while some cetaceans, especially dolphins and killer whales (odontocetes), also emit and detect sounds at high frequencies (up to 200 kHz). Whales are able to communicate over long distances using low frequency sounds (Duarte *et al.* 2021). Blue whales (*Balaenoptera musculus*) and common rorquals (*Balaenoptera physalus*) look for the water current with the most appropriate temperature to ensure that their songs are transmitted to other ocean basins, in order to be heard by conspecifics up to 4000 km away (Tsuchiya *et al.* 2004).

Animals emit sounds for a variety of reasons: orientation, feeding, territoriality, attracting a mate or warding off a competitor. Whales produce low-frequency calls for reproductive and social purposes. The humpback whale (*Megaptera novaengliae*) sings complex songs that can change over time and even between different regions, like dialects. Not only large cetaceans are capable of complex behaviours. Recently, a species of crab (*Maja squinado*) was found to emit sounds when it detects the proximity of food, probably to warn its conspecifics. Some animals produce sounds related to feeding behaviour, such as parrotfish that scratch the surface where they are feeding. Surprisingly, sea urchins also produce a characteristic sound when they graze on algae on the rocky substrate. These sounds allow researchers to identify different individuals. Even more surprising is the case of the scallop (*Pecten maximus*), which produces different noises when it moves (swimming by propulsion) and when it feeds (filtering water), so its behaviour can be determined through its sounds (Busson *et al.* 2010).

The sound of revolution

Since the Industrial Revolution, all these sounds have been accompanied by the sounds produced by human activity, such as shipping, fishing, seismic prospection, dredging, military operations and seabed mining. All these activities have been adding noise pollution to the natural sounds of the marine environment (Figure 1). Anthropogenic noise affects marine animals negatively (Duarte *et al.* 2021). In many cases, the frequency band of the noise overlaps the one emitted by the animals, preventing intraspecific communications. Shipping noise disturbs ma-

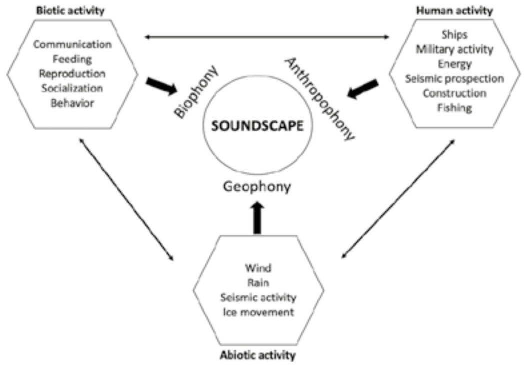

Figure 1. Various components of the marine soundscape, which is the sum of the sounds caused by organisms (biophony), meteorological and geological phenomena (geophony) and humans (anthropophony).

rine mammals' activities, such as feeding, socialization, communication, navigation and resting. It can attenuate the anti-predator behaviour of juveniles of some fish species, increasing their mortality and reducing their ability to learn predator avoidance behaviours (Duarte *et al.* 2021). It is also capable of disturbing the settlement and development of larvae and juveniles of some invertebrate reef species, which use the reef soundscape to locate appropriate settlement places (Lillis *et al.* 2018).

The degradation of marine habitats, such as kelp forests, seagrass meadows and coral reefs, leads to a decrease in the soundscape of these ecosystems owing to a decrease in the abundance of sound-producing animals. In addition, seagrass meadows (e.g. *Posidonia oceanica*) and gorgonian forests can have a noise-attenuating function, creating oases of calm for the species taking shelter inside them.

In the last 50 years, the growth of commercial shipping has increased low-frequency noise along major shipping routes by a factor of 30 (Figure 2). Furthermore, overfishing has decreased the population of several fish and mammal species, impoverishing the soundscape to which they contribute. Climate change also affects the sounds of the seafloor. Rising water temperatures, increasing stratification and modified currents can alter the speed and distance at which sound is transmitted, with consequences for marine animals. Increased CO_2, which causes ocean acidification, results in a noisier ocean, leading to a substantial decrease in sound absorption by the ocean at frequencies below 10 kHz. Moreover, the higher frequency of extreme climatic events and heat waves linked to climate change leads to the degradation of marine habitats and the alteration of their biophony (Duarte *et al.* 2021).

Experts are proposing measures to mitigate anthropogenic noise, which are already being implemented in some marine protected areas (MPAs). In the Cinque Terre MPA in Italy,

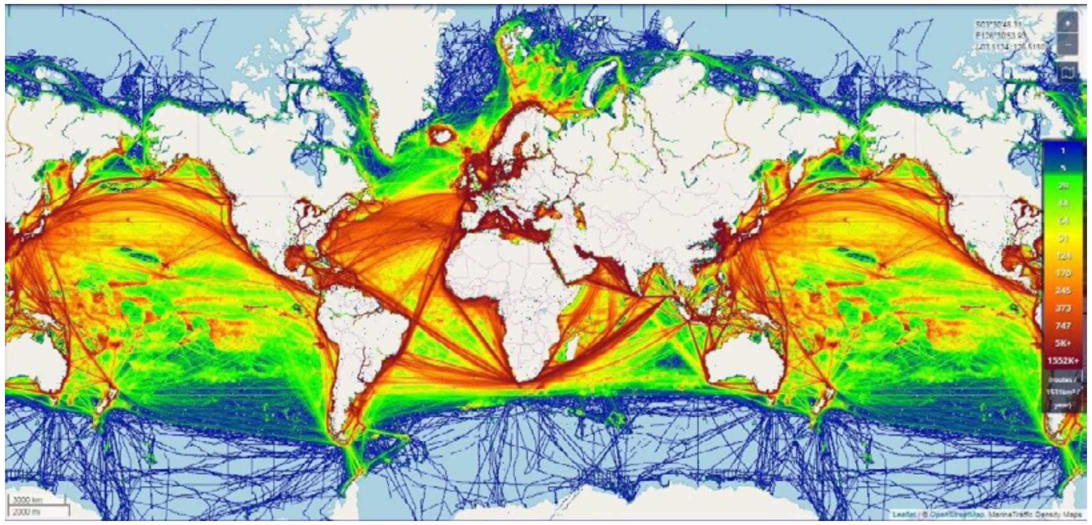

Figure 2. World shipping traffic map (https://moverdb.com/shipping-traffic-density/).

navigation permits are given on the basis of the noise produced by the boat, rewarding the less noisy ones. In France, in the Cerbere/Banyuls MPA, a study of the songs of groupers (*Epinephelus marginatus*) and croakers (*Sciaena umbra*) has been carried out in order to regulate night SCUBA dives during the seasons when these species sing for reproduction. In the Cap de Creus and the Medes Islands MPAs, navigation speed has been limited to reduce noise and its impact on the soundscape of the no-take zones. It has been estimated that reducing speed by 2 knots reduces the broadband ship noise by 50%.

Despite some initiatives at the local level, underwater noise pollution is a fact that has not yet been taken into consideration in national and international environmental policy objectives, but we will probably start to hear more about this topic in the future, and the "background noise" will be heard by the whole population.

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1.5. Marine litter, the new plague of seas and oceans

Eve Galimany, Elena Marco-Herrero, Montserrat Ramón

Seas and oceans represent most of planet Earth. The good health of their waters is crucial to sustaining life, not only of aquatic ecosystems but also of terrestrial ones. But this health is threatened by what's called marine litter, the remains of all kinds of objects and materials, which are currently one of the main causes of pollution, creating severe environmental and economic problems around the world.

The great majority of marine litter comes from land-based activities, where waste is transported to the seas and oceans by wind, rivers, rain and a lack of proper management for a currently overpopulated Earth. Of the different types of marine litter that reach seas and oceans, including fabrics, paper, batteries and glass, the majority (61% –87%) is made up of plastic. This plastic, with dimensions ranging from microns (microplastics) to centimeters and occasionally meters (macroplastics), ends up on the seabed where they are perpetuated for years, even centuries.

Marine litter and its effects

The effects of marine litter are diverse and alter both organisms and communities and also the economic activities generated by these ecosystems. To date, effects have been described in 1400 species distributed worldwide (Galgani *et al.* 2019). Some of the most common physical effects observed in the fauna are entanglement, when they are entangled with marine litter, and starvation, when they ingest litter and it accumulates in the digestive systems preventing feeding and, even, damaging organs. In addition, plastics often carry chemical additives that can be toxic and bioaccumulate along the food chain. Economically, marine litter has very negative effects due to the increased cost of cleaning both the body of water and the beaches. Moreover, marine litter can generate costs in maritime economic sectors caused by the impacts on the ships' hulls and breakage of fishing gear, even ruining cooling systems and engines.

How is the Mediterranean Sea doing?

The Mediterranean Sea, which has culturally and traditionally supported all the civilizations that have occupied its shores, is especially vulnerable to the effects of marine litter. The Mediterranean geomorphology makes it a very closed sea, where the waste is trapped with almost no option to disperse and leave. It is because of the large accumulation of marine litter that it is currently considered one of the dirtiest seas on the planet (Galgani *et al.* 2014).

The exact amount of marine litter in the Mediterranean is difficult to assess due, among other things, to the fact that most research has been done mostly at depths >100m. The first study that quantified the amount and type of marine litter found on the seabed in shallow depths was recently published in 2019 (Galimany *et al.* 2019). By collaborating with shellfish fishers that worked between 10 and 68 m deep in Catalonia, the marine litter present in the catches was quantified in two areas, an urban one, located just south of Barcelona, and a rural one in the Ebro Delta (Figure 1). Results showed that, in areas close to heavily populated locations (Urban Zone) and with busy shipping routes, marine litter can account for 37.6% of

Figure 1. Image of the catch obtained by the artisanal fishery in the urban area (left) and in the rural area (right).

the total catch by weight per sampled area (Figure 2). In terms of mass densities, it represents between 198 and 393 kg of litter per km². In contrast, marine litter fished off the coast of less populated areas (Rural Zone) accounted for 5.2% of the total catches, which are much lower densities (34 and 56 kg of litter per km²) than in the urban areas.

Once marine litter has reached seas and oceans, it is very difficult to remove because

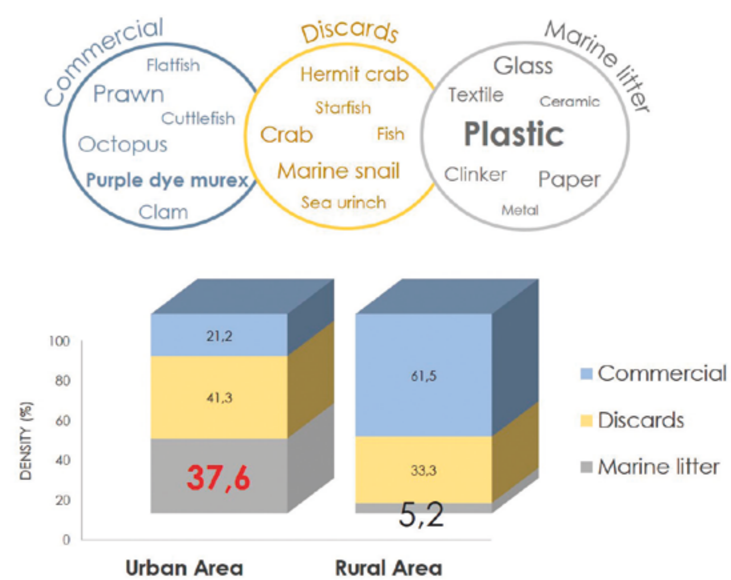

Figure 2. Comparison of the mass density (kg m^{-2}) in the percentage of marine litter catches, discards (organisms without commercial value) and commercial fraction in the artisanal fishing "rastell de cadenes" between the urban and rural area.

the drift and the spatial immensity through which they move, including great depths, make it extremely difficult to find an effective and economical solution. In addition, there are no efficient methods or strong legislation to clean the seabed. Thus, the best waste is that which is not generated and, for this, there must be a common effort of the population to break the current trend of waste production. Simple acts such as recycling, reuse of resources and a change in the habits of the population, especially with regard to the excessive use of plastic, can greatly help reduce the litter that reaches the sea. For that litter that have already accumulated in the depths, mechanisms could be established for collaboration with fisheries so they could help eliminate the litter that they accidentally catch on a daily basis. This would reduce fishing costs and potential hazards to marine ecosystems.

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1.6. International strategies and challenges for society to achieve a plastic-free ocean

Cristina Romera-Castillo, Vanessa Sarah Salvo

The Plasticene, the Age of Plastics, began in the 1950s as a result of the exponential increase of the production and consumption of plastic products (Corcoran *et al.* 2014). Since this period, plastic waste has started to undergo a process of geological stratification and fusion with rocks, creating specific conglomerates called “plastiglomerates”, which are proposed as stratigraphic indicators of the Anthropocene. It has been demonstrated that of the total amount of plastic produced, only 9% has been recycled; 12% has been incinerated and 79% is now in landfills and in the environment (Geyer *et al.* 2017). In 2020 a production of 350 million metric tons of plastic was declared by the industry, of which 5% ends up in the sea. Estimates of plastic production indicate a continuous growth of this sector and therefore an intensification of its impact on the sea.

As a result of exposure to sunlight, erosion and oxidation, the plastic in the coastal environment breaks down into pieces of less than 5 mm, some of them fibres and nanoparticles that are invisible to the naked eye. Marine litter affects the marine ecosystems with aesthetic, physical, chemical and biological impacts and is a concern for human health through ingestion of seafood and drinking water contamination (figure 1).

The chemical additives of plastic are another cause for concern. These are chemical compounds added to the polymers to enhance their physico-chemical characteristics such as strength and performance, or to colour them. These additives can easily be diluted in the environment, affecting the carbon cycle and the microbial trophic chain (Romera-Castillo *et al.* 2018). Some of these additives are very toxic for humans and marine sea animals. In some cases, they are persistent substances that are transferred up the food chain and gradually accumulate in the top level through a process called biomagnification. In addition, plastic can absorb chemical pollutants from surrounding waters, reaching high concentrations of toxic substances. When plastic is eaten by animals, these additives and/or pollutants can leach into their stomachs, leading to neurologic and endocrine system disorders and cancer.

International strategies

At an international level, marine litter has been recognized as a critical issue, in particular because of its abundant plastic component. In 1995 the Global Programme of Action for the Protection of the Marine Environment from Land-Based Activities of the United Nations Environment Programme set up voluntary agreements to deal with the problem of marine litter. The Honolulu Strategy of 2012, resulting from the Fifth International Marine Debris Conference, represented a comprehensive, global effort to reduce the impact of plastic. The international community currently agrees on the urgency of tackling plastic pollution as one of the main threats to the planet. Several declarations, recommendations and decision have been ratified at international level. These include Sustainable Development Goals 12 and 14 of the United Nations 2030 Agenda and the urgent calls to action of the G7 Action Plan to Combat Marine Litter (2015) and the G20 Action Plan on Marine Litter (2017). In 2018

Figure 1. Single use plastic in marine ecosystem. © The Ocean Agency-Ocean Decade.

the European Plastics Strategy was adopted. It includes recommendations, lines of action and measures for the coming years. Directive (EU) 2019/904, known as the Single-Use Plastics Directive, has been transposed at national and regional level, in some cases with a delay because of COVID-19. One of the first places where the Directive was implemented was the Balearic Islands (Law 8/2019 of the 19 February). This regional regulation was an example for all EU Member States, as it proposed more ambitious objectives than the Directive. However, despite the urgent calls to action, there are still several open questions. Research is needed to help decrease the impact of plastics through new data, materials and technologies.

Solutions

Many ideas for cleaning plastic from the ocean have been proposed during the last few years, but they will be in vain if new plastics are not prevented from entering the sea. Closing the plastics tap is the main measure to take at a global level. The plastic waste flowing into the ocean from land-based anthropogenic sources represents 80% of the total amount. Several of the solutions offered are curative, i.e. they are applied at the end of the chain of production and consumption, but changes should be made at the source of the impact. Some examples of curative actions are the new technologies linked to valorization, reuse and recycling of plastics, and their replacement by other materials. Studies that are underway seek to use specialized bacteria for plastic biodegradation or propose chemical recycling as a potential alternative to incineration. Data are still lacking to obtain a detailed picture of the impacts created by plastics and the direct and indirect impacts of these solutions. Nevertheless, it is clear that the health of humans and the earth are in danger. It is time for citizens, governments and scientists to make a collective effort to overcome the Plasticene with strong prevention measures and actions.

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Photo: Stefano Ambroso

2. Healthy and resilient ocean

Clara Ruiz-González, Enrique Isla, Joan Navarro

We live surrounded by nature even though we do not always know how to appreciate its greatness. The oceans, which we perceive as homogeneous water masses that provide us with food and fun, hide infinite secrets that are only revealed through the detailed observation and study of their properties, their inhabitants and the delicate balances that maintain their functioning. Our actions and our way of living against (and not with) nature are endangering this balance and thus the health of the oceans, and we are not fully aware of the negative repercussions that a sick ocean could have on our lives and on the habitability of the planet.

There is an urgency to understand that it is time to protect and look after this great source of life, as well as to promote actions that allow its recovery. Human action, which can cause so much harm, is also capable of achieving positive changes if the efforts are directed towards the recovery and restoration of ecosystems, populations and communities of organisms. This requires a deep understanding of how the ocean works and of its ability to respond to the changes that have happened or are expected to happen in the coming years.

The study of the oceans encompasses countless disciplines, ranging from the ecology of planktonic microorganisms, which control the global cycles of chemical elements and maintain large marine mammal populations and fisheries, to the regulation of global climate through the movements of currents and water masses. However, despite the huge advances in our knowledge of the oceans, we are still far from having all the tools needed to preserve, restore and protect the oceans from the problems we are generating. Only by learning to look at the oceans with the respect, admiration and dedication they deserve will we be able to stop degrading them and understand that we are nothing without them.

2.1. The planetary organism

Josep L. Pelegrí

A lifetime of studying the oceans has given me the opportunity to gaze into their complexity and intelligence. Initially I focused on analysing some of their components separately –such as currents, mixing processes and primary production– but over the years I discovered that their beauty and richness lies in their complementarity, in their interconnections, in their role in generating the earth's complexity.

In 2008, I presented a physiological approach to the oceans that proposes that the oceanic circulation system pulses in a similar way to the circulatory system of complex entities such as mammals (Pelegrí 2008). A simple physiological model explained the variations in atmospheric CO_2 between glacial and interglacial periods during the last three million years. The model was later adjusted with genetic algorithms, showing that the natural oscillation of atmospheric carbon can be justified as a result of the transformation between the organic and inorganic forms of dissolved carbon in the oceans (Pelegrí *et al.* 2013). In physiological terms, the heart of the ocean beats annually, each winter driving the planetary circulatory flow through the sinking of surface waters at high latitudes. This circuit is very active in interglacial times –with a high metabolism that transforms large amounts of carbon and inorganic nutrients via photosynthesis– but slows down during glacial periods –a resting phase with the storage of dissolved organic matter as a form of energy in reserve.

Recently, we have explored the idea that ocean and atmosphere maximize the flow of energy, just as living beings do (Roca and Pelegrí 2020). Under this premise, we have developed a planetary energy model that correctly reproduces the climatic trends between the last glacial maximum and the present and makes reasonable predictions about the evolution of the planet's temperature by the end of the century. A corollary of this study is that the Earth has spatial patterns that are similar to those observed in species that have evolved over time, and that these patterns optimize the flow of life-sustaining properties such as water, nutrients and energy (Figure 1).

A new view of Gaia

These conceptual studies on temporal and spatial physiological patterns, together with many observational and numerical oceanographic works in different regions of the planet, allow us to reinterpret the complexity of the ocean planet. Starting with a brief reminder of the Gaia hypothesis and appealing to the vision of life as a process, we can reexamine the fundamental role of water and oceans on our planet.

During the 1970s, James Lovelock and Lynn Margulis proposed that life intervenes in the creation of the planetary environment: the physical environment is regulated in such a way that the development of life is optimized (Lovelock and Margulis 1974). This proposal –the Gaia theory– generated a new look at our planet but failed to enthuse a large part of the scientific community owing to the apparent practical impossibility of verifying it. Despite some valuable efforts during the last decade (Stephen Harding; Eileen Crist and Bruce Rinker; and Carlos de Castro), the predominant approach to our planet is currently systemic: a set of differentiated entities that interact and self-organize, giving rise to collective properties more complex than those of its parts.

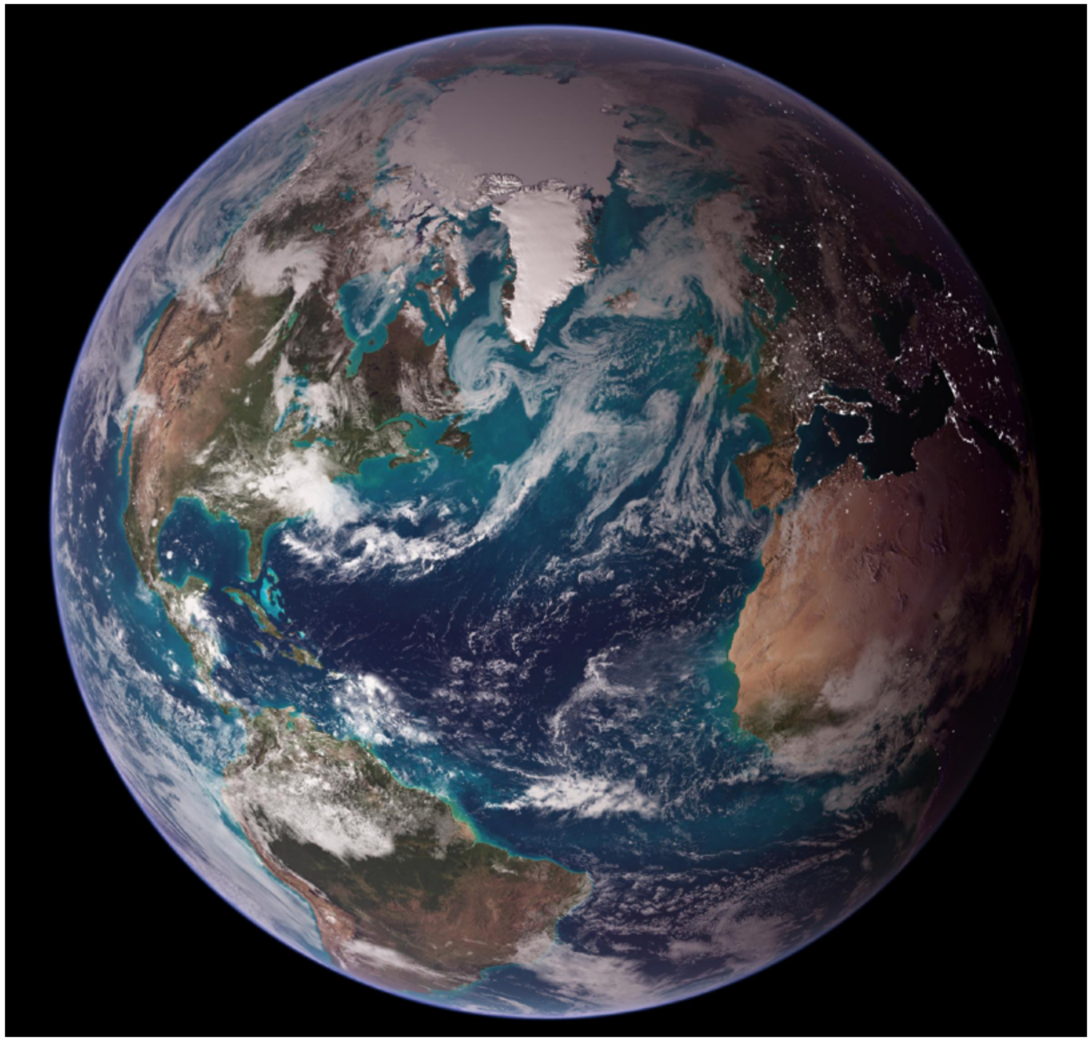

Figure 1. A satellite image that gives an insight into the complexity of the atmosphere and the surface of oceans and continents on planet Earth. Goddard Space Flight Center, NASA.

At the present time, when the Gaia ideology seems to have given way to the pragmatism of big data and artificial intelligence, it is surprising to see how many programmes and organizations take the symbolism of the living planet as their motto (e.g. Living Earth, Living Planet and Living Ocean). These programmes arise from our new ability to observe almost the entire surface of the planet with great precision (Figure 1); what was previously remote and inaccessible appears close and the image of familiarity is transmitted. However, these programmes focus more on dissecting the building blocks (the physico-chemical environment, individuals and communities and ecosystems) and understanding the interlocks between differentiated entities than on exploring the holistic idea of a living planet.

Life as a process

The classical vision of life is based on substance: the material living being develops complex functions in an apparent internal balance within defined physical limits. This living being –physically differentiated, connected and trapped in a limited space– organizes and regulates itself, responding and adapting to external stimuli.

An opposite view of life is based on dynamic processes that, through a continuous flow of properties, lead to an apparently stable system (Nicholson and Dupré 2018). This is what we usually call a homoeostatic system, but it goes far beyond a complex, self-organized system, because it is constantly evolving. The flow of matter, energy and information creates complementarity and resilience, maximizing complexity and minimizing disorder (entropy).

Temporarily, some portions of the system exhibit a high degree of organization, but these regions completely renew their matter in much shorter cycles. Human beings, for example, renew all of our cells in periods much shorter than the length of our life. From the substantial perspective of life, we call these regions individuals, but under the processual approach, the spatial and temporal restriction of the individual disappears and the differentiated entities are seen only as a static image within the continuous flow of processes.

Life as a process opens a new perspective to the Gaia hypothesis. It can be stated with certainty that no part of the earth system, including humans, is closed. Only the biosphere, with the oceans as an essential and central element, is truly independent, an entity of immeasurable complexity that for millions of years has operated and evolved using practically only solar energy.

Planet Ocean

In the flow of matter, energy and information –the flow of life–, water is an indispensable chemical compound. More than a century ago, Lawrence Henderson (1913) highlighted its wonderful thermal and solvent properties (of carbon, nutrients and salts, among others). Recently, Gerald Pollack (2013) emphasized its occasional crystalline behaviour, with surprising spatial and temporal affinities.

Water, which connects the most distant places on the planet as a liquid solvent or as a solute (liquid in the subsoil and gaseous in the atmosphere) also reaches the tiniest spaces where the molecular processes that enable our existence take place. The flow of water between the environment and entities, whether ecosystems or individuals, appears at all scales: from the formation of the oceans by the impact of comets and meteorites and the recycling of carbon thanks to the lubrication of tectonic plates to the transformation of solar energy into chemical energy through photosynthesis and the biogeochemical cycles responsible for maintaining the volume of planetary water.

To speak of the hydrological cycle is to speak of oceans, and to speak of oceans is to speak of life. The oceans are means, structure and purpose. They contain 97% of the liquid surface water in our world and are the largest repository of the properties vital for life, with over 95% of the planetary metabolic activity. Ocean fronts and currents establish the physical and biogeochemical environment, characterizing regions and defining the degree of connection between ecosystems. As a result, the different oceanic regions have complementary physiological roles that enable the planetary organism to function (Pelegrí 2019).

The living ocean is no longer a metaphorical phrase, it becomes a reality made up of much more than individuals, communities and marine ecosystems. The flow of matter (water and biogeochemical properties) is accompanied by that of energy (in all its forms, from internal and mechanical to chemical, stored as organic matter) and information (genetic, environmental and communities). Hence the search for living exoplanets begins with the identification of planets with liquid water.

Thanks to the oceans, thanks to the flow of water and its multiple properties, we are all interconnected with our environment and with each other. Life as a process questions individuality: matter, energy and information are part of the universal flow, and this has been the case for about four billion years of planetary life. Each one of us is part of the planet, though at each moment we manifest ourselves with a high degree of organization in an apparently limited space.

The future of humanity in harmony with its environment lies in our ability to develop a planetary consciousness. The health of the planet depends on the health of each of its parts and, vice versa, the health of the entire planetary organism is what will bring us health here and now. The COVID-19 pandemic and the climate emergency are clear examples that health and planetary awareness go hand in hand.

This essay is the adaptation of an article published in The Conversation on September 3, 2020 under the title "Planet ocean: the liquid heart that keeps us alive" (https://theconversation.com/planeta-oceano-el-corazon-liquido-que-nos-mantiene-vivos-145553).

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2.2. The impact of the Southern Ocean on climate

Anna Olivé Abelló, Josep L. Pelegrí

The Southern Ocean is defined as the ocean region that encircles and partly isolates the Antarctic continent from the warmer subtropics. The intense westerly winds raise the deep dense waters towards the south, and this phenomenon has two main effects. First, it leads to the eastward Antarctic Circumpolar Current (ACC), the planet's most intense, longest and deepest current, which connects the three major ocean basins, helping to establish the global overturning circulation (Figure 1). Second, it permits the direct interaction between the atmosphere and the deep waters, regulating the exchange of mass, heat, salt, carbon, oxygen and other properties between the lower and upper layers of the global ocean (Figure 2).

Additionally, deep waters are formed over the Antarctic continental shelf. The sinking of dense waters, together with the wind-induced rise (upwelling) of subsurface waters, leads to the formation of vertical recirculation patterns, which are known as the lower and upper subantarctic vertical cells (Figure 2). The upwelling branch of both cells raises the old deep waters between 30°S and the Drake Passage –depleted in oxygen and enriched in dissolved inorganic carbon and macronutrients– to the upper ocean. In turn, the downwelling branches deliver heat, oxygen, anthropogenic carbon and other properties into the deep ocean interior.

The Southern Ocean is a site for the development of polynyas, which are ice-free regions of deep-water formation and enhanced primary production. But possibly even more important, the Southern Ocean stores and transports key physical and biogeochemical properties to the

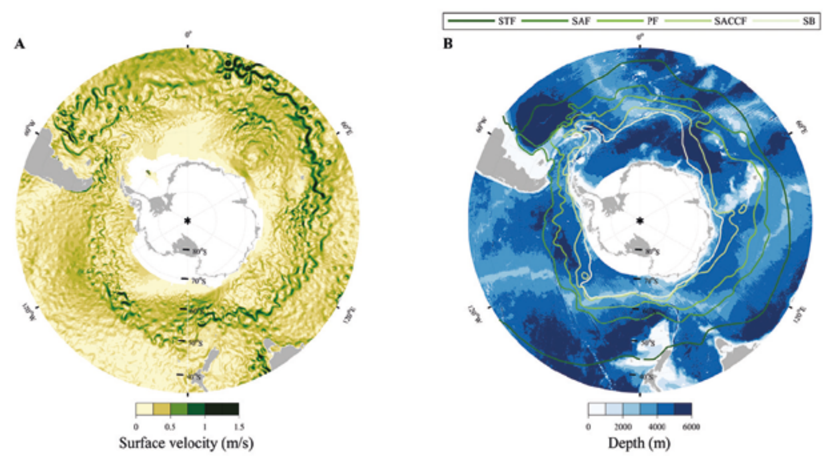

Figure 1. A, a daily image (30 May 2020) of the sea surface eddy-rich structure in the Southern Ocean, as deduced from a 0.25° resolution dataset that combines satellite data with numerical model products. B, bathymetry and position of the ACC fronts as determined by Orsi *et al.* (1995), from north to south: Subtropical Front (STF), Subantarctic Front (SAF), Polar Front (PF), Southern ACC Front (SACCF), and Southern Boundary (SB) of the ACC.

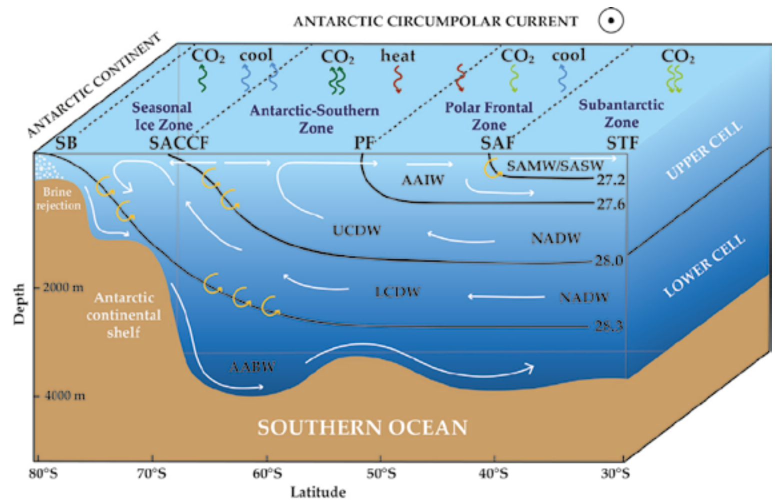

Figure 2. A schematic meridional section in the Southern Ocean showing the water masses according to their neutral density (kg m^{-3}), the meridional-vertical cells, and the main heat release/uptake zones relative to the circumpolar fronts. The water masses are Subantarctic Mode Water (SAMW), Subantarctic Surface Water (SASW), Antarctic Intermediate Water (AAIW), Upper Circumpolar Deep Water (UCDW), Lower Circumpolar Deep Water (LCDW), Antarctic Bottom Water (AABW) and North Atlantic Deep Water (NADW).

various ocean basins, with a profound influence on climate. The intensity of the zonal ACC and its vertical cells turn the Southern Ocean into a major climate regulator.

A regional and global heat regulator

During sea ice formation, salt is expelled to the underlying seawater in a process called brine rejection. This causes an increase in the density of the shelf waters and leads to mixing and vertical convection, which originates the cold and dense Antarctic Bottom Water (AABW). Once formed, the AABW migrates northward following the topography, and is a major factor for maintaining the abyssal regions cold (Carter *et al.* 2008).

The intense zonal winds shape the deep circumpolar waters to produce the ACC fronts, which are regions with maximum latitudinal density gradients and peak zonal currents (Figure 1). These frontal systems are also the main sites for the upwelling and downwelling branches of the upper and lower vertical cells (Figure 2). Waters upwelling between the southern ACC Front and the Polar Front are transformed into lighter surface, mode and intermediate Antarctic waters, which will be transported northward and will sink (a process named subduction) between the Polar Front and the Subtropical Front (Rintoul 2018).

One consequence of the subduction process is the summer release of atmospheric heat to the ocean interior, which balances the heat lost to the atmosphere at lower latitudes. It has been estimated that the Southern Ocean accounts for about 75% of the anthropogenic heat uptake since the preindustrial period, hence acting as a very efficient global-warming regulator.

On the other hand, the subduction of light waters compensates for the southward mass transport of deep (relatively warm and salty) waters that originated in the North Atlantic Ocean. As these northern waters reach the Southern Ocean, the intense upwelling brings them to the surface layers. One consequence is the shelf ice melting causing the formation of coastal polynyas and the decline of the shelf ice thickness.

Interactions between ice melting, surface albedo and sea-level rise

Global climate and sea-level rise are largely regulated by two-way ocean-cryosphere interactions in the Southern Ocean. Seawater warming is a driving force for the melting of shelf ice, consequently influencing the freshwater budget, impacting the stability of the Antarctic ice sheet and potentially controlling the contribution of the Southern Ocean to the global overturning circulation.

Changes in the extension of sea ice also influence the Earth's surface albedo, defined as the proportion of solar radiation that is reflected by land, ocean or ice: the whiter the surface, the higher the albedo. The Antarctic region exhibits one of the largest albedo variations on Earth, associated with the seasonal expansion and contraction of sea ice. Reductions in sea ice extent will drive both a decrease in albedo, so the Southern Ocean will take up more solar radiation, and an increase in the temperature of the surface waters, which is known to diminish the water's capacity to absorb carbon dioxide (Rintoul *et al.* 2010).

The evolution of the Antarctic ice sheet, the Earth's largest land ice reservoir, is still largely unknown, as it depends on the incorporation of atmospheric excess heat, of anthropic origin, but also on a complex combination of different factors. An increase in snow precipitation (higher albedo) and a decrease in the intensity of the Southern Ocean vertical cell (less warm waters reach the region) will favour the sustenance of continental ice. In contrast, the reduction of surface albedo and the melting of coastal subsurface ice will lead to the reduction of the ice sheets over Antarctica (DeConto *et al.* 2021).

An important global role in the carbon cycle

The Southern Ocean stands out as a major site for storing the excess of anthropogenic CO_2. The net exchange of carbon is determined by the balance of two competing effects: the natural outgassing at the highest latitudes, where the carbon-rich deep waters approach the atmosphere, and the subduction of anthropogenic carbon, especially in the subantarctic Zone (Figure 2). The outcome is the ocean's uptake of about 1 Pg C/year, which represents over 40% of the intake of anthropogenic carbon dioxide by the global ocean (Rintoul *et al.* 2010).

Primary production from photosynthetic organisms consumes the limited amount of inorganic nutrients available at the sea surface. The intense upwelling in the Southern Ocean is the main return path for nitrate, phosphate and silicate from the deep to the upper ocean, sustaining the elevated level of primary production. When the ACC fronts interact with bathymetry, the iron-rich sediments also emerge and are exported thousands of kilometres offshore. As these nutrients are incorporated by the subantarctic Mode Waters, they support about 75% of the ocean primary production north of 30°S, becoming a substantial sink of atmospheric CO_2 and a source of oxygen to our atmosphere (Sarmiento *et al.* 2004).

The above ideas suggest that the deep and cold Southern Ocean is both a barrier and a connector. It is a barrier to the iced Antarctic continent but, possibly even more important, a region that stores and distributes massive amounts of key climatic properties. This connectivity with all major ocean basins sets the Southern Ocean as an essential agent in the fluxes and storage of energy at global scales, ranging from primary production to climate, in what may be understood as the planetary metabolic system.

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2.3. Life in the oceans: from the magic of the stars to the scientific knowledge of plankton

Magda Vila, Vanessa Balagué

The beginning of everything started with the great explosion from which the stars and, later, the planets were formed. The great ball of fire, which millions of years later we would call planet Earth, cooled and solidified until, when it was cold enough, the water vapour condensed and flooded the large basins, giving rise to a vast expansion of water that we would call the ocean. The primitive atmosphere would have been unbreathable for the majority of living beings today: it was a reducing atmosphere formed mainly by methane (CH_4), ammonia (NH_3) and water vapour (H_2O), and over time it became enriched with other gases from volcanic activity.

Life! From the first forms to the current ones

Time went by, and about 3,800 million years ago the first forms of life originated. It was microscopic and very simple life, anaerobic (living in the absence of oxygen in the air), and it began to populate the water systems. Prokaryotic cells, without a differentiated nucleus, were the only inhabitants of the planet for several million years. Living beings were evolving and diversifying in morphology (coccoid, bacillary and spiral) and size. Their metabolic routes also diversified and, around 2,700 Ma, some of these microorganisms, the cyanobacteria, began to produce their own food by capturing carbon dioxide (CO_2) from the environment and, using energy from the sun, transforming it into organic matter (sugars), water and a waste material that was highly toxic to the primitive inhabitants, oxygen (O_2) (Cermeño 2020). They had invented photosynthesis. Time continued to pass, and, little by little, these ancestors transformed the primitive atmosphere into an oxygenic atmosphere which finally gave rise to the current gaseous mass with a predominance of nitrogen (N_2, 78%), oxygen (O_2, 21%), argon (Ar, ~0.9%) and carbon dioxide (CO_2, ~0.04%). There is little scientific knowledge about the formation of eukaryotic cells with a differentiated nucleus, but in 1967 Lynn Margulis, a revolutionary scientist, proposed a theory about the origin of eukaryotes based on symbiosis as an evolutionary mechanism (Margulis 1998, Cornejo and Pita 2022). The symbiotic theory postulates that chloroplasts (the plant organelles that allow photosynthesis) and mitochondria (the energy factories of cells with a nucleus) are the result of successive symbioses of prokaryotes that gave rise to the eukaryotic cell. We do not yet know when, where and how eukaryotic cells evolved, but today there is no doubt that symbiogenesis played a key role in the evolution of life into more complex forms. Some of these complex marine organisms colonized the landmass, and a few (e.g. seagrass and whales) returned to the sea. But we will skip this part of the story to move to today's ocean.

Plankton: the engine of ocean life

What is in this immense liquid ecosystem? We know that there are many fish of different sizes, shapes and colours, birds that depend on them, large mammals, reptiles, invertebrates, many strange-shaped organisms, animals that look like plants (corals), plant life that is so small that it cannot be seen (phytoplankton), and tiny crustaceans that feed on them (zooplankton). But we will stop there, and go on to explain about this little-known world of plankton. Plankton means wandering, and it is because plankton is made up of all the world's aquatic organisms that drift or float in the water with a limited capacity for movement, so they are unable to overcome the force of waves and currents but are carried away by its swaying and by oceanic circulation. Plankton (Figure 1) is made up of very small, microscopic organisms, but also much larger ones such as jellyfish and fish larvae and numerous marine invertebrates (such as larvae of sea urchins, starfish and sea cucumbers, corals and gorgonians) (The Sea in Depth: https://elmarafons.icm.csic.es/la-xarxa-trofica). The primary producers formed by nanoalgae and microalgae (phytoplankton) and by autotrophic bacteria (cyanobacteria) play an important role. And this is the magic of these organisms that produce organic matter, without which there would not be the food needed by the rest of the marine (or terrestrial) organisms: the consumers (herbivores and carnivores). Therefore, simplifying, we say that phytoplankton is at the base of marine food webs (Estrada 2013). Furthermore, without oxygenic organisms, we would not enjoy an atmosphere with enough O_2 to allow us to breathe. A considerable part of this oxygen comes from the sea, produced in ancient times by the invisible microorganisms of plankton. But we are not finished yet: plankton also have

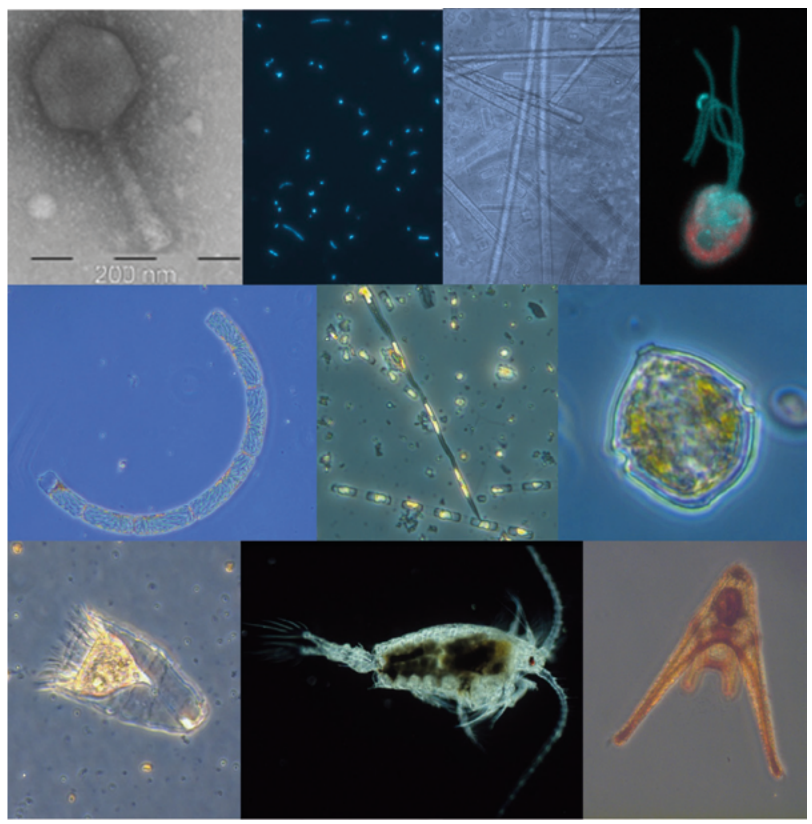

Figure 1. Photocomposition of various microscopic organisms of marine plankton. From left to right. Above: the virus *Myovirus* (Elena Lara and Dolors Vaqué), bacteria (Irene Forn and Ramon Massana), filamentous cyanobacteria (Magda Vila) and autotrophic flagellate (Irene Forn). Middle: the diatom *Guinardia striata* (Laura Arin), diatom chains of the genera *Pseudo-nitzschia* and *Skeletonema* (Magda Vila) and a dinoflagellate of the genus *Scrippsiella* (Magda Vila). Bottom: a ciliate tintinnid (Albert Calbet), the copepod *Centropages typicus* (Albert Calbet) and sea urchin larvae (*Paracentrotus lividus*) (Marc Mascaró and Magda Vila). The sizes of the microorganisms range between 200 nm and 2 cm.

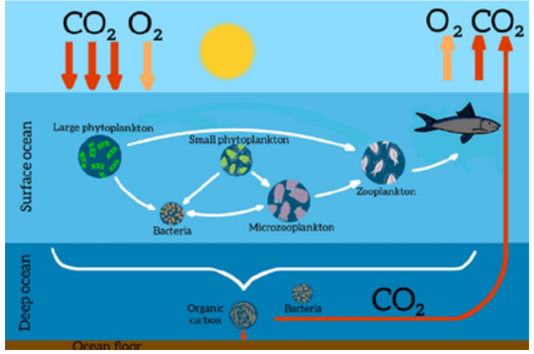

Figure 2. Simplified diagram of the microbial food web and the biological carbon pump in the ocean. Figure adapted by Helena Galán from Chisholm (2000).

a primary role in regulating atmospheric CO_2, which worries us so much because it is one of the main greenhouse gases that are responsible for the global warming that our planet suffers. When the primary producers of the sea carry out photosynthesis, they trap carbon in the form of CO_2 from the atmosphere to build their cellular structure. When they die or are consumed by zooplankton and/or lysed by viruses, their components end up being remineralized by bacteria and fungi, and all of them form the microbial food web (Chisholm 2000). However, a small part of the carbon escapes from this web of life and accumulates at the ocean bottom, where it remains immobilized for thousands and thousands of years. This is what is known as the biological carbon pump, which is of paramount importance because it reduces the return of carbon to the atmosphere in the form of CO_2 and therefore helps reduce global warming (Figure 2). If it were not for the transcendental role played by the ocean in capturing CO_2, its atmospheric concentration would be higher than the current one and consequently so would the average temperature of the planet.

The wide variety of organisms that make up plankton and the enormous variety of marine organisms are critical for a healthy and resilient ocean. High biological diversity often gives an ecosystem the necessary strength to resist the damage caused by a disturbance, whether natural or anthropogenic. Under strong stress, natural and diversified communities are replaced by a few organisms that reproduce excessively, producing a change from complex communities to highly simplified ones that are often almost monospecific. This is the case of some phytoplankton blooms and large proliferations of jellyfish that, in recent decades, have increased in frequency, intensity and temporality. Since its creation, the Institut de Ciències del Mar (ICM), initially with the collaboration of Ramon Margalef and several of his students, has been a leader in the study of the organisms that form part of plankton and in understanding the mechanisms that regulate their dynamics and the biogeochemical processes in which they are involved.

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2.4. Microorganisms in a changing ocean

Maria Montserrat Sala, Josep M. Gasol, Ramon Massana, Dolors Vaqué

Life came to earth almost four million years ago, when primitive microorganisms appeared in the middle of sulphurous oceans and toxic skies. That the air we have today is breathable is mainly due to microorganisms, which have been evolving and changing our planet for billions of years until we now have enough oxygen for our lives (Figure 1) (Vila and Balagué 2022). Because of their enormous genetic variability and rapid growth, microorganisms have a great capacity to respond and adapt to new environmental conditions. Lately, however, marine microorganisms are facing a series of unprecedented environmental changes, many of them associated with human impacts, and their responsiveness will be key to sustaining life in marine ecosystems (Hutchins and Fu 2017).

Marine microorganisms form very diverse and productive communities that include phytoplankton, protists, fungi, viruses, and the two main groups of prokaryotes, bacteria and archaea. Their importance for the ocean is evident from the total number of cells (10^{29}) and the fact that 70% to 90% of the biomass in the sea is microbial. Though they are microscopic and invisible to the eye, they play a key role in

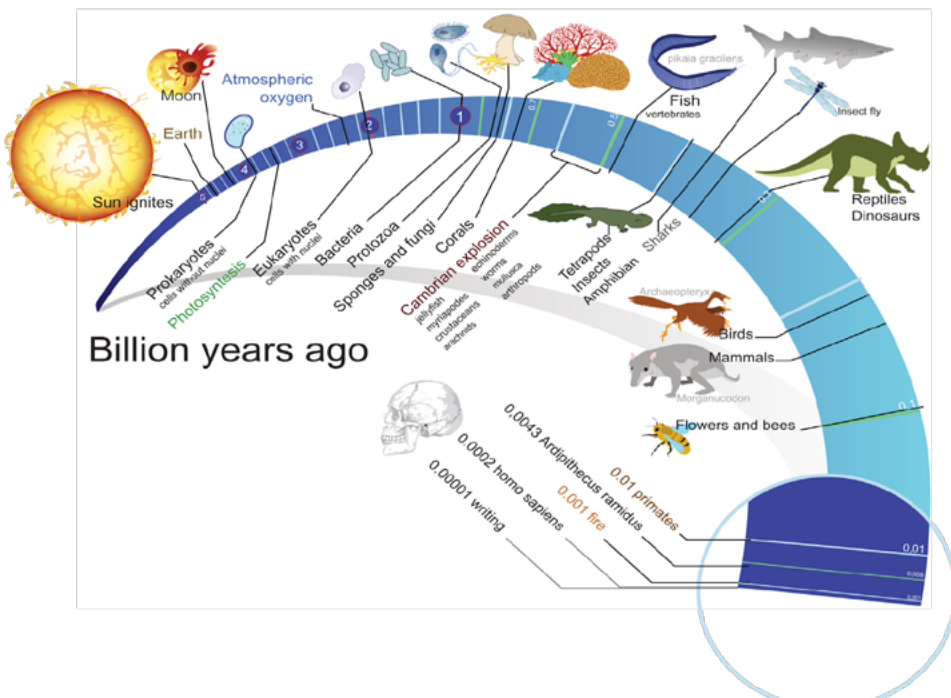

Figure 1. Different phases of life evolution on the planet, showing their microbial, specifically prokaryotic, origin. Source: Creative Commons CC0 1.0 Universal Public Domain Dedication.

biogeochemical cycles. For example, microbial transformations of nitrogen in the ocean contribute greatly to nitrogen fluxes, and microorganisms play a central role in the carbon cycle because they participate in the biological pump that sequesters CO_2 from the atmosphere in the deep ocean.

The effects of global change on marine microorganisms are key for the ocean

The global change that the earth has been experiencing in recent decades is leading to a warmer, more acidic ocean as a result of rising temperatures, the accumulation of CO_2, the melting of the poles, and the increase in the stratification of the water column, which results in the expansion of oxygen-depleted areas. Debates about global change often ignore microorganisms, probably because they are not as visible as polar bears and whales, and they do not have the commercial importance of fish. The impact of global change on marine microorganisms can, however, have important consequences for the ocean, including changes in productivity and trophic networks and the export of carbon to deep sediments (Cavicchioli *et al.* 2019).

Global change alters the interactions between species and forces them to adapt, migrate or become extinct. Microorganisms can disperse more easily than larger organisms (Ruiz-González *et al.* 2022), and their rapid reproduction gives them high adaptive potential. However, little is known about the mechanisms of physiological response to global change and their implications for biogeochemical cycles. For example, there is no clear information on the trend of phytoplankton in recent decades, often owing to a lack of data, which is why we need to strengthen the time series (Massana *et al.* 2022). However, experiments seem to indicate that the impact of global change will be negative on coccolithophores, unicellular algae that are characterized by plates of calcium carbonate of uncertain functionality which dissolve at low pH (Figure 2A, B). It appears that primary production will increase or decrease depending on the ecosystem, but the dominance of small primary producers such as cyanobacteria (Figure

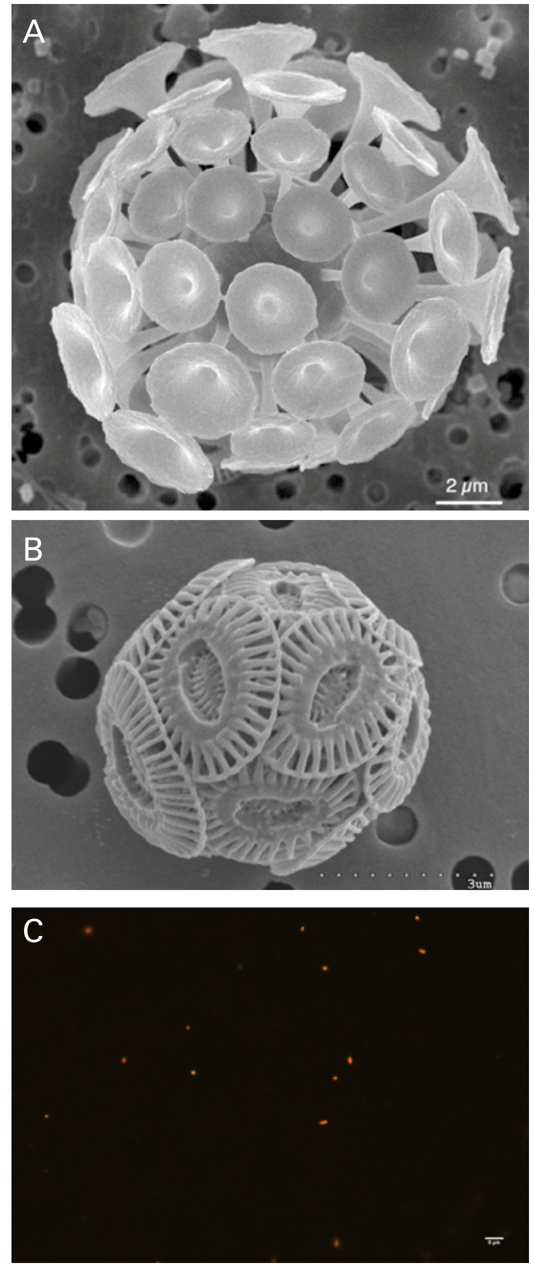

Figure 2. Electron microscopy images of two coccolithophores, Discosphaera tubifera (A), and Emiliania huxleyi (B), that will be negatively affected by global change. Optical microscopy image of Synechococcus (C), a cyanobacteria that will be favoured by global change. Photos: Lluïsa Cros and Dolors Vaqué.

2C) over larger phytoplankton microorganisms will be favoured. This decrease in the size of the primary producers of the ocean can have serious consequences for the planet, because their sedimentation and therefore the sequestration of atmospheric carbon to deep sediments will be reduced.

The effects of global change on microorganisms have generally been studied in short, week-long or month-long experiments (e.g. Sala *et al.* 2016), but given the ability of microorganisms to adapt to changing environmental conditions, long-term studies are needed in which different environmental factors are combined to obtain more robust results and allow us to predict the ecological consequences.

Human impact and microorganisms in the ocean

Another component of global change, especially in recent decades, is the negative impact of human activity on the coast, causing eutrophication, blooms of toxic algae and hypoxia (Berdalet *et al.* 2022). Discharges of toxic substances and the accumulation of marine litter, around 80% of which is plastic, have also increased (Morales-Caselles *et al.* 2021). Plastics have an almost ubiquitous presence in the sea, in sea ice and in sediment, and it seems that their concentration will double in the next ten years. These plastics fragment into microplastic particles that are colonized by microorganisms, forming what is called the "plastisphere", which makes them more palatable for consumption by larger organisms and allows them to pass to higher levels of the food web (Amaral-Zettler *et al.* 2020), causing problems in various groups of animals. In addition, because these particles are poorly biodegradable, they act as a vehicle for transporting microorganisms between ecosystems, which can encourage the spread of pathogenic microorganisms and the introduction of invasive species. One of the scientific challenges of the future to contribute to the reduction of plastics on the planet is the isolation of microorganisms with enzymes capable of accelerating the biodegradation of microplastics.

Future challenges for marine microbiologists

The main challenge for marine microbiologists in the coming decades will be to predict the response of microorganisms to the environmental alterations caused by global change in terms of specific species and their interactions, how this response will affect the biogeography and structure of communities and, above all, the extent to which oceanic biogeochemical cycles will be affected.

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2.5. A microbial ocean with no boundaries: connecting microorganisms within and beyond the marine environment

Clara Ruiz-González, Marta Sebastián, Josep M. Gasol

Wherever you look there is life that you cannot see. On your hands, your table, your computer, the floor, the grass, the air and the water. Microbes thrive in all kinds of habitats, including our own body, and despite their insignificant size, they are responsible for biogeochemical processes of global importance. The ocean is no exception, as most marine life is actually microbial, and seawater is essentially a soup of drifting microorganisms. Among these, the tiniest living beings are bacteria and archaea. With around 10^{29} estimated cells in the ocean (more than stars in the universe), and 10^{10} different species, both the chemistry and the life in the ocean are largely controlled by microbial activity and their interactions with other planktonic creatures: they divide and grow, eat each other, respire and die, and during these processes they produce, consume and transform an enormous diversity of chemical elements. For example, a large fraction of the oxygen we breath was produced by the activity of small photosynthetic bacteria that are now very abundant in the sunlit ocean (Vila and Balagué 2022). In fact, without them, we would not even be on this planet.

As microbial ecologists, we are interested in understanding how these marine microorganisms interact with the environment. To this end, we investigate shifts in the composition of microbial communities and their functions along environmental gradients, as well as the main factors controlling the abundance of bacterioplankton, such as bacterial predators and viruses. However, we are far from understanding the consequences that changes in microbial communities may have on the health of ecosystems, including the ocean, mostly because most of the species are still unknown and we are just starting to learn what they do in their natural environment.

The surprising ubiquity of microorganisms

During the last few decades, we have become increasingly efficient at characterizing the microbial diversity hidden in natural samples by sequencing their genetic material (because unfortunately it is not possible to distinguish these organisms morphologically), and hundreds of studies have enquired whether microbial communities show spatial and temporal patterns such as those reported for animals and plants. In the ocean, these studies have shed light on the complexity of marine microbial life. We now know that some bacterial species can occur as individual cells (freely suspended in the water), whereas others prefer living attached to dead organic material or other organisms; we know that microbial communities change pronouncedly with depth, because the dominant species in the surface are very different from those in the deep ocean; and we observe that microbial communities change seasonally in a succession of taxa that repeats itself year after year. Moreover, these sequencing approaches have allowed us to discover the existence of an enormous diversity of marine bacterial species present in very low numbers that had not been detected

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before. These rare species play crucial roles in bioremediation processes and restoring ecosystems upon disturbances, such as oil spills and storms, holding a vast biotechnological potential (Gasol *et al.* 2022).

The detection of the rare species revolutionized the field of microbial ecology by radically expanding their perceived areas of distribution. Many bacterial species appear to be everywhere and seem able to persist inactive in a state of "dormancy" out of their preferred habitats for very long times (even thousands of years!), until they encounter favourable conditions for growth (e.g. Sebastián *et al.* 2019). This impressive capacity for persistence means that microbial dispersal may be more important, and that microbial communities may be much more connected, than was previously believed.

Limitless dispersal within and outside the ocean

Scientists are beginning to discover and characterize previously unknown dispersal pathways (Figure 1A). For example, we recently found that microbial communities from the deep ocean are strongly connected to the surface, because sinking organic particles transport attached microorganisms (Mestre *et al.* 2018). This finding led us to the surprising discovery that surface conditions and surface biota are strong determinants of the deep ocean microbi-

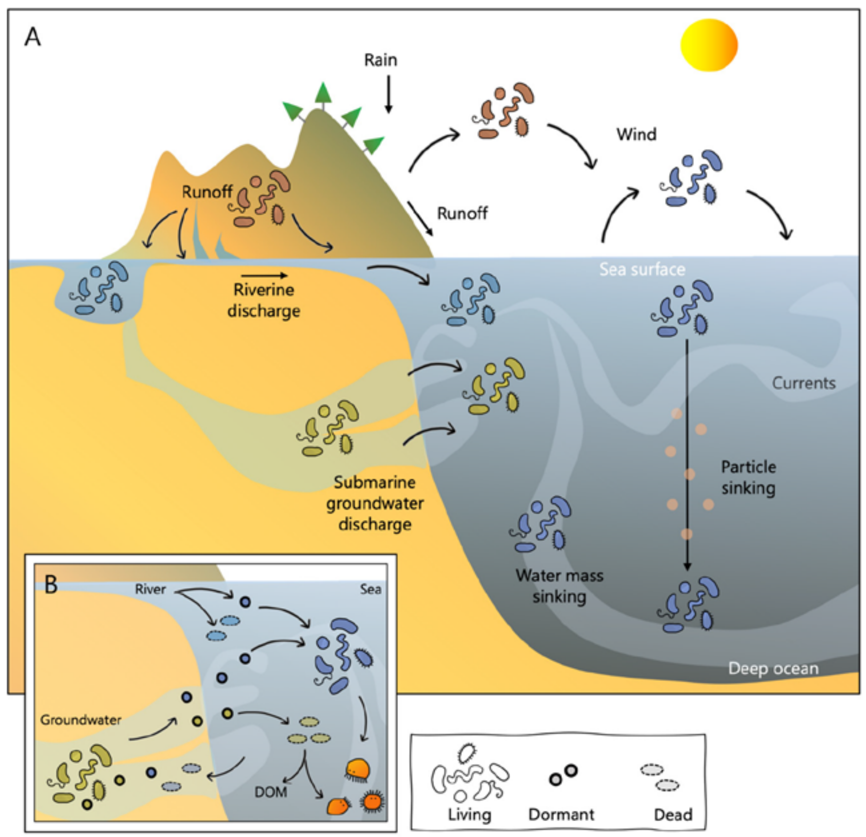

Figure 1. A, main microbial dispersal routes within and between the ocean and other ecosystems, highlighting that the interactions between microbial communities transcend ecosystem boundaries (modified from Ruiz-González 2020). B, the inset shows that this dispersion can result in activation of dormant species and/or inactivation (or death) of live taxa owing to the change in conditions. This might have consequences for ecosystems and food webs, e.g. through the release of carbon and nutrients from dying cells or the ingestion of allochthonous cells by other marine bacterial predators (orange creatures). DOM, dissolved organic matter.

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Life in the oceans
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A microbial ocean with no boundaries
Proliferations of photosynthetic organisms
Symbiosis
Fish in the face of global change
Marine predators in the Anthropocene
Ecological integrity of the seabed
The changing colours of Antarctic marine life
Restoration of deep ecosystems on the Catalan margin
Fishermen and scientists
Looking with remote eyes
Renewable maritime transportation
Adapting beaches for the future

ome (Ruiz-González *et al.* 2020). Scientists have also found that sinking water masses and currents can move microbes throughout the ocean, and that wind can transport marine microorganisms across thousands of kilometres, linking remote oceanic regions (Mayol *et al.* 2017) and perhaps explaining the ubiquity of certain marine bacterial species.

This microbial ocean, however, is not isolated from the surrounding terrestrial or freshwater ecosystems. Enormous amounts of water and material are transported to the ocean from rivers, runoff and other hydrologic pathways such as groundwater discharge; indeed, microbial activity in coastal sediments, estuaries and the sea largely controls the flow and fate of the chemical elements transported by the water. But this continental water also transports microorganisms. The importance of these dispersed microbes in the ocean is not yet known, but recent evidence from freshwater systems suggests that it may be significant: in lakes, bacterial communities are profoundly influenced by the transport of microorganisms from the surrounding terrestrial landscape, because some can grow and dominate the aquatic environment (Ruiz-González 2020). Marine microbial ecology must therefore consider all these linkages with terrestrial and freshwater systems, but this is rarely done and fundamental questions remain open: Can these microorganisms thrive in the ocean and impact the cycling of chemical elements? Scientists have shown that it is possible to experimentally recover living marine bacteria from lake sediments and the air, which suggests that freshwater or terrestrial ecosystems harbour dormant marine bacteria waiting to be awakened in seawater conditions. Can these transported species serve as additional food for marine microorganisms feeding on bacteria or archaea? This would imply a so far neglected source of external carbon and energy in marine food webs (Figure 1B)! Are we detecting "foreign" microbial species that are not functioning in the ocean and are thus obscuring our interpretation of microbial patterns? And the questions continue…

Microbial landscapes are much more complex than we tend to think, and they are by no means isolated. Understanding the functioning and threats of the ocean requires moving beyond its boundaries and considering the complex linkages between the microscopic engines that drive our planet. Only then will we be able to have a predictive understanding of how the future ocean might behave when facing any of the possible scenarios in the years to come.

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2.6. Proliferations of photosynthetic organisms: two sides of the pillars of marine ecosystems

Elisa Berdalet, Laura Arin, Magda Vila, Laia Viure

Photosynthetic organisms form the basis of the food webs and are the pillars of terrestrial and aquatic ecosystems. Photosynthesis is performed by pigments (chlorophyll, carotenoids and biliproteins; e.g. Berdalet 2020) that capture light energy to incorporate CO_2, synthesizing organic matter and producing the oxygen we breathe.

The dynamics of proliferations of photosynthetic organisms

Photosynthetic organisms are very diverse. In the aquatic environment, they include multicellular and macroscopic organisms such as macrophytes (posidonia) and macroalgae (sea lettuce and nori seaweed), in addition to unicellular and microscopic organisms (microalgae and certain bacteria). Sargassum and microphytoplankton float and are transported by currents, whereas the vast majority of macroalgae, macrophytes and the microphytobenthos live attached to the sea bottom. Photosynthetic organisms also participate in the biological carbon pump, which removes atmospheric CO_2 and buries it at the ocean floor, thus contributing to climate regulation (Vila and Balagué 2022, Segura-Noguera *et al.* 2022).

The growth of photosynthetic organisms is marked largely by latitude and seasons. In addition, in the aquatic environment, water motion and currents determine the availability of light and nutrients. For example, in seas of temperate latitudes, such as the Mediterranean (Estrada 1999; Estrada *et al.* 2022), the proliferation of phytoplankton, mainly diatoms (Figure 1), occurs in late winter–early spring. Diatoms grow in illuminated and turbulent layers (Alcaraz and Estrada 2022) containing nutrients supplied by water mixing during the autumn-winter seasons. Gradually, the surface water warms, and being less dense, it is separated from the deep layer by a density and thermal gradient (a pycnocline). In the surface layer, phytoplankton grows by consuming nutrients. When these are scarce,

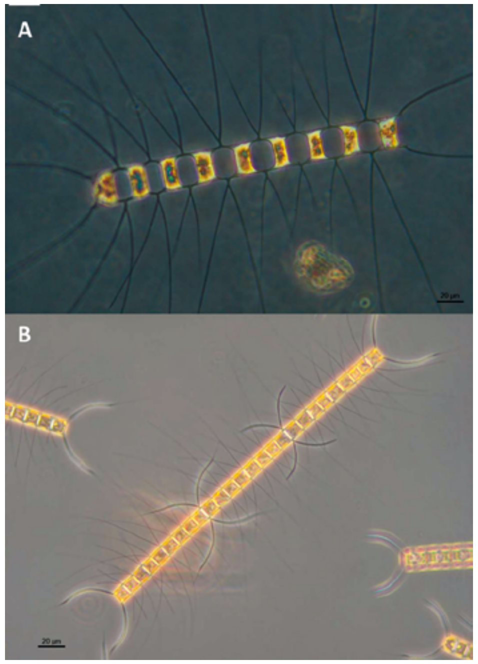

Figure 1. Two species of diatoms of the genus *Chaetoceros* are generally abundant in late winter and early spring proliferations in the Mediterranean. A, *C. decipiens*. B, *C. affinis*. Photos: L. Arin.

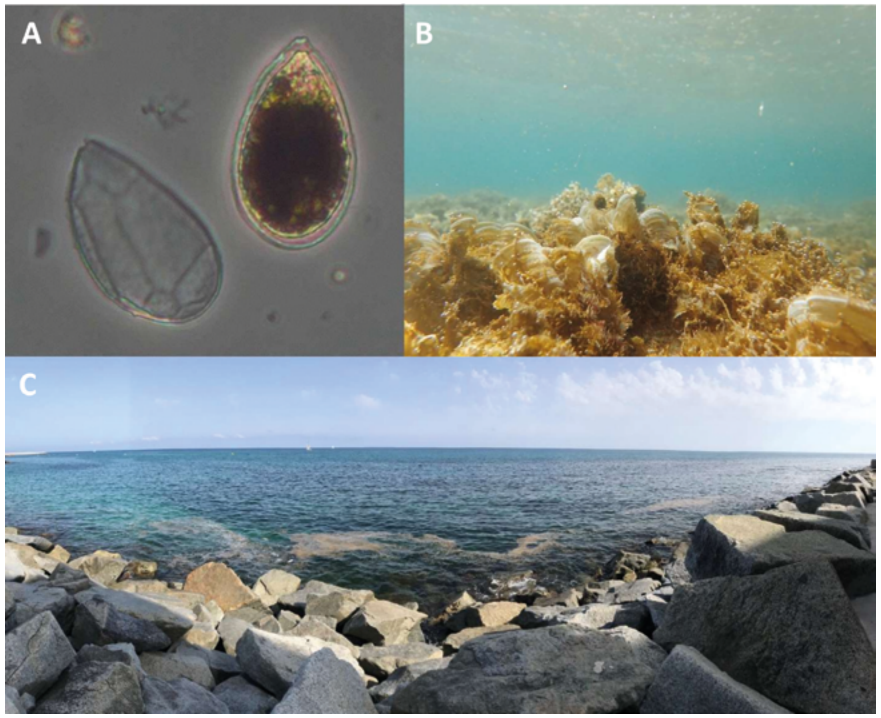

Figure 2. Proliferation of the benthic dinoflagellate *Ostreopsis* cf. *ovata* (A) on the Catalan coast in summer. Cells adhere to macroalgae (B) and are also detached in aggregates that float on the surface (C) and show the reddish colour of the microalgae's photosynthetic pigment peridinin. Photos: E. Berdalet, L. Viure and M. Vila.

other microalgae such as dinoflagellates proliferate; these cells have the ability to migrate vertically, performing photosynthesis at the surface and obtaining nutrients from deeper layers near the pycnocline. In the pycnocline, sinking phytoplankton can accumulate for density reasons, and the deep chlorophyll maximum (DCM) is formed if enough light from the surface and nutrients from the deep layers reach the pycnocline by diffusion or small-scale mixing. The depth of the DCM varies according to the area of the ocean and the dynamics of stratification and vertical mixing; in summer it is highly productive. Progressively, the organic matter produced within the food webs settles to deep layers and is remineralized by bacteria, that is, consumed and transformed into organic molecules, and especially into inorganic salts.

Autumn storms return nutrients from deep waters to the surface and the seasonal cycle restarts. Also, on the western coasts of the continents, upwelling of nutrient-rich deep water favours phytoplankton production and with it the richness of the marine ecosystem that supports large fishing grounds.

Harmful algal blooms (HABs)

So far, the positive aspects of the proliferation of photosynthetic organisms have been summarized. However, in certain circumstances the rapid growth and reproduction of some micro- or macroalgae species cause "harmful algal blooms" (HABs), which have negative effects on humans and the environment. Of the several thousand species of microalgae described, about 300 are involved in HAB phenomena and about 100 produce toxins. HABs are often favoured by the combination of high nutrient availability from natural or anthropogenic sources and low hydrodynamics (relatively calm or low water turnover). In these situations, a few species reach concentrations in the water above a species-specific "normal" level. HABs can lead to changes in the colour of the water (Vila and Torán 2002), which takes on the colour of the pigment of the proliferating organism (green, blue, yellow, brown or red). In brackish water or freshwater, blue-green cyanobacteria often proliferate, whereas proliferations of the microalgal group of dinoflagellates form "red tides". These blooms are relatively common in summer, particularly in enclosed, nutrient-rich habitats with long water residence times, and often with resting cysts (cells that can survive in winter or during nutrient limitation periods) in the sediments, which constitute a reservoir of cells ready to germinate and proliferate when conditions are appropriate.

Some of these species produce toxins that are transferred through food webs and contaminate seafood (fish, shellfish) and can cause poisoning in humans who ingest them, leading to amnesia, diarrhoea, paralysis, etc. Other toxins (microcystins) contaminate drinking water, others (ovatoxins and brevetoxins) are transferred to aerosols and cause respiratory irritation, and yet others affect humans by direct skin contact with water (in this case the toxic agent is not well determined). Often, the excess biomass of algae cannot be consumed efficiently by the components of the trophic foodwebs (microzooplankton, fish larvae, small crustaceans, etc.), and their degradation by bacteria leads to decreased levels of oxygen in the water and a deterioration in the quality of the ecosystem in general.

HABs have economic costs, including those of medical care and of monitoring and controlling toxic microalgae and their toxins. Some microalgae (*Chattonella antiqua*, *Fibrocapsa japonica*, *Chrysochromulina* spp., *Cochlodinium* spp. And *Karlodinium* spp.) specifically kill fish in natural habitats or aquaculture zones. In shellfish production areas, the presence of potentially toxic algae (e.g. *Dinophysis acuta*, *Alexandrium minutum* and *Gymnodinium catenatum*) leads to a ban on the extraction and sale of shellfish, resulting in economic losses. On the other hand, when algae die, their degradation by bacteria decreases the quality of beach water and leads to health problems that have direct impacts on tourism. The massive accumulation of *Sargassum* macroalgae on the beaches of the Caribbean and West African coasts is an emerging case of HABs that started 10 years ago.

The problem of HABs has gained prominence in the last 40 years all over the world. Anthropogenic pressure on coasts and oceans (habitat destruction and loss of biodiversity, eutrophication and urbanization) and global warming favour the increase in HABs in certain areas (Vila *et al.* 2021). Protecting and sustainably using the environment is key to reducing this trend and ensuring a healthy and resilient ocean.

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2.7. Symbiosis: a source of innovation for surviving a challenging ocean

Francisco M. Cornejo-Castillo, Lucía Pita

At first sight, the ocean could seem a vast homogeneous soup of salty water in which quietness, harmony and peace have prevailed over the history of life, but nothing is further from reality. The ocean is a challenging environment whose inhabitants, encompassing both microscopic and macroscopic living forms, have been (and still are) in a constant struggle to thrive and survive. In this daily battle, cooperation between different biological species (i.e. symbiosis) develops innovative strategies for succeeding in such a dynamic system. Here, we will explain the importance of maintaining a healthy relationship with the oceans, illustrating with examples what marine symbioses can teach us about the past, the present and the future of the oceans.

Marine symbioses: breakthroughs in the history of life on Earth

One of the major revolutions in biology was postulated in the Theory of Endosymbiosis by Lynn Margulis (1938–2011), who proposed that organelles (e.g. chloroplasts and mitochondria) within eukaryotic cells (i.e. cells with a true nucleus such as animal and plant cells) originated from the engulfment of one bacterial cell into another. These evolutionary events allowed new metabolic functions to be generated and compartmentalized within eukaryotic cells (e.g. aerobic respiration in mitochondria and photosynthesis in chloroplasts). Although the underlying processes remain difficult to address because they occurred over geological timescales, the outcome is obvious: the rise of complex forms of life, including all known multicellular plants and animals. Since then, all these organisms (including humans) have lived and evolved by forming alliances with microbes, even delegating to them key functions such as nutrition or defence.

The wide spectrum of symbiotic interactions currently found in the ocean, from obligate to facultative, offers an uncountable variety of biological innovations (Figure 1). Among the extant single-celled symbioses (symbioses between two species whose whole body is formed by only one cell), one interesting case is the widespread marine partnership between a coccolithophore microalga (*Braarudosphaera bigelowii*) and a nitrogen (N_2)-fixing cyanobacterium (i.e. one that is capable of converting atmospheric N_2 gas into bioavailable nitrogen) called UCYN-A (Figure 1A) (Foster and Zehr 2019). The discovery of UCYN-A unveiled that it has features typical of organelles, including a reduced genome compared with its sister species and, interestingly, the loss of typical cyanobacterial functions such as the capacity to perform photosynthesis. The extraordinary parallelism between the endosymbiosis that gave origin to the chloroplasts and the UCYN-A symbiosis therefore provides a window to the past for understanding the early evolution of chloroplasts present in current algae and plants.

Let us take as another example one of the most ancient animal groups that are still existent: sponges (Figure 1B). Marine sponges appeared on our planet 600 million years ago (Mya) (about 300 million years before the first trees grew on land) and, with the help of their microbes, they have conquered almost all aquatic habitats. As in the human gut, their

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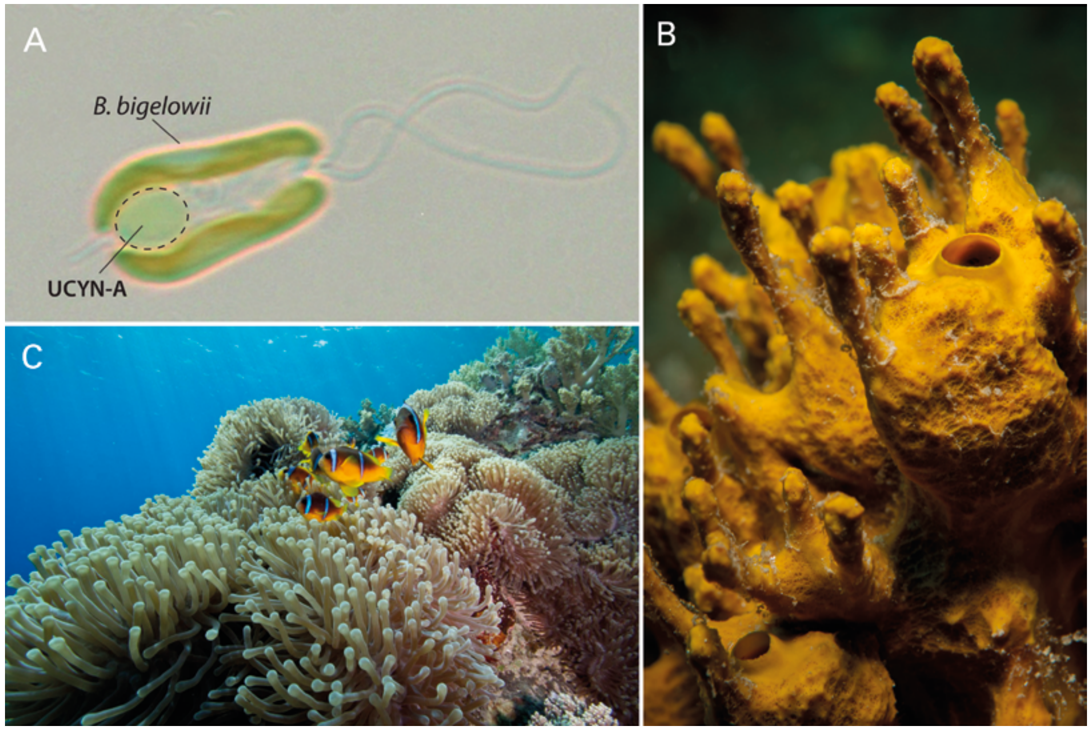

Figure 1. Examples of marine symbioses. A, the UCYN-A and *B. bigelowii* nitrogen-fixing symbiosis (total magnification of the image: 1000×) (photo credit: Esther Wing Kwan Mak). B, sponges, a unique microbial factory (photo credit: Jordi Regàs, https://www.cibsub.cat/guia.php). C, symbioses make up coral reefs (photo credit: annaroik.org).

microbiota provides nutrients and defence to the sponge host (Pita *et al.* 2018). Some of the microbes produce special compounds with biotechnological applications, such as antitumoral drugs. In addition, sponges harbour bacteria and viruses that are not found anywhere else! Thus, losing a single sponge species means losing a unique microbial factory. Because of their ancient origin, sponge-microbe symbioses teach us about how animals interact with the microbial world. From sponges to humans, decoding this animal-microbe dialogue is key to understanding animal health.

The ecological significance of marine symbioses, a lifestyle for survival in a challenging ocean

The activity of microbial symbionts soaks through the walls of their hosts and scales up to the ecosystem level via huge transformations of matter and energy that affect global biogeochemical cycles (McFall-Ngai *et al.* 2013, Pita *et al.* 2018), and in the ocean we find prominent examples of symbiosis-driven ecosystems.

For example, nitrogen is an essential element for primary productivity, but it is scarce in many regions of the ocean. In these systems, N_2-fixation can provide the highly needed bioavailable nitrogen, but it is exclusively performed by some bacterial species. Thus, some marine species (mostly phytoplankton) have found a way to thrive in nitrogen-depleted environments like the sunlit open ocean by partnering with N_2-fixing symbionts. The N_2-fixing cyanobacterium UCYN-A became symbiotic with *B. bigelowii* during the late Cretaceous, around 100 Mya (Cornejo-Castillo *et al.* 2016). This is interesting, because between 190 and 100 Mya, nutrient availability in the ocean was lower than at any point during the last 550 million years. It is therefore likely that this peculiar symbiosis between UCYN-A and *B. bigelowii* enabled them to cope with extremely low nutrient conditions and a generalized oligotrophy in marine surface waters.

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On the seafloor (benthos), sponges filter hundreds of litres of water per day, taking the nutrients they need and releasing their waste products into the water. The activity of their microbes determines the nutrient budget and, coupled with the enormous pumping capacity of the sponge host, defines the ecological role of sponges in the cycling of nutrients.

In hydrothermal vents, the fissures in the ocean floor that discharge hot and toxic geothermal water, microbes detoxify harmful substances and provide energy and nutrients for animals such as worms, mussels and shrimps. Due to these symbioses, highly diverse and productive communities flourish in this extreme environment.

Finally, in nutrient-poor marine waters, other photosynthetic microalgal symbionts, the dinoflagellates, provide corals with the carbon they need to build the skeleton that creates the coral reef, which is home to multiple marine species. Coral reefs (Figure 1C) are hotspots of biodiversity, and millions of humans depend on them.

Hence, in times of struggle, go find a microbial partner!

Symbiosis has benefits and costs, but evolution finds the balance that promotes the success of the interacting species. Currently, human activities are modifying nature at an unprecedented pace, putting that balance at risk. In the ocean, global warming, pollution, and nutrient enrichment are killing entire populations of marine species. Rapid changes in the environment affect host-microbe interactions and can contribute to susceptibility to disease in both marine organisms and humans. In the examples presented in this essay, we show how ancient marine organisms succeeded with their microbes in responding and adapting to the surrounding environment. Marine life offers us a journey to our evolutionary past and tells success stories that relied on strengthening cooperation with others of a different kind, which is crucial for facing our current and future challenges.

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2.8. Fish in the face of global change: the importance of early life stages for conservation of natural populations

Ana Sabatés, M. Pilar Olivar, Vanesa Raya, Joan Mir-Arguimbau, Ainhoa Bernal

The early life history of fish is the period that elapses from spawning to recruitment into the adult population (Figure 1). These early stages –eggs and larvae– are a key component in the fish life cycle because their survival success determines both short- and long-term variations in population abundance. Most marine fishes produce thousands to millions of pelagic eggs, which in a few days hatch into larvae that spend weeks to months in the plankton. Fish larvae are characterized by their small size (a few mm to ca. 2 cm), transparency and limited swimming skills, and they display amazing shapes that differ greatly from those of adults (Figure 2). During the planktonic period, fish larvae interact with other planktonic organisms as both predators and prey (Figure 1): feeding upon small prey such as juvenile stages of copepods and, in turn, being preyed on by larger nektonic and planktonic organisms such as jellyfish. The mortality of fish eggs and larvae is extremely high, and only a few individuals from thousands of newly hatched larvae survive the ever-present threats of starvation and predation during their planktonic life (Houde 2009). Physical factors such as currents, fronts and eddies, which determine larval dispersal and concentration, are also major controllers of larval survival (Catalán *et al.* 2006). Therefore, the interaction between the physical environment and larval biology control inter-annual variations in fish recruitment and ultimately influence the persistence of the adult populations.

Fish spawning strategies

Fishes have evolved a variety of spawning strategies adapted to specific features of the habitats so that offspring are placed within environments that allow the best chance of successful feeding, growth and survival, as well as population connectivity (Sabatés *et al.* 2007). Temperature, along with photoperiod, is the primary environmental factor that controls the seasonal window for reproduction. Although some degree of flexibility is displayed in spawning times in response to inter-annual changes in water temperature, most species have relatively fixed spawning seasons. This flexibility will

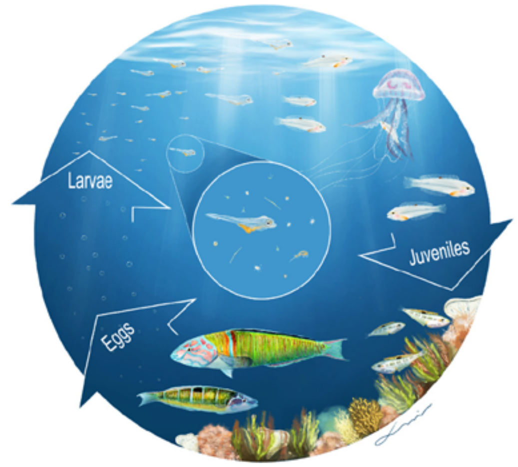

Figure 1. Schematic representation of the ornate wrasse life cycle.

Figure 2. Larvae of a spinyfin fish of the family Diretmidae (left), mesopelagic fish of the family Scopelarchidae (centre) and flat fish of the family Bothidae (right)

likely allow fishes to adapt to climate-driven changes to ensure matches of offspring with prey in altered (e.g. warmer) environments. Fish populations 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. Shifts in the physical and biological environment can therefore disrupt species-specific synchrony with optimal conditions for embryonic development, larval feeding, growth and favourable transport or retention into nursery habitats.

Impact of climate change on early life fish stages

The impact of climate change on early life stages of fish is not yet well understood, but could be foreseen from what we know of the biology of these stages. While no direct lethal effects are to be expected for the currently observed temperature increase, indirect effects through changes in their habitat suitability and food supply are more likely. Elevated ocean temperatures are predicted to affect the composition and size of plankton communities, thus changing the suitable prey field for fish larvae. Greater thermal stratification of the water column will reduce nutrient availability to the surface layers, limiting primary production and zooplankton abundance, with the consequent lower performance of larval fishes. In addition, temperature increase will lead to increased larval growth and, as a result, a shorter planktonic larval duration, which may result in the alteration of connectivity patterns between spawning and nursery grounds. However, little is known on the relative importance and potential interacting effects of the ocean warming and changes to food supply on the performance of larval fishes.

Under climate change, fishing is likely the most significant anthropogenic impact on fish, and its effect on the early life history stages is the result of demographic changes in the adult populations. The number and quality of eggs produced depend on the age or size of the spawners, with older or larger fish producing many more eggs and spawning earlier than smaller fish. High exploitation rates result in age-truncated populations with fewer older fish, which are mainly composed of juveniles with low reproductive potential. These changes in the demographic structure would reduce the reproductive potential of the fish population and alter the phenology (time and duration) of the spawning season.

Fish early life history studies in the NW Mediterranean

Studies on the early life history of fish have been recognized as an important part of the research carried out at the ICM since the 1970s. The Mediterranean Sea, our nearest system, has received special attention. The Mediterranean is one of the most impacted seas in the world, since climate change interacts synergistically with many other anthropogenic factors such as fisheries overexploitation, pollution, biological invasion and habitat loss, which often co-occur in time and space and have cumulative effects. Long-term changes in the hydrodynamic and meteorological conditions, with warming air and water, stronger and longer stratification, lower wind speed and progressive water acidification have been reported in the Mediterranean. In the western basin, a decrease in the river run-off waters, in particular from the Rhone and Ebro, and a decrease in chlorophyll *a* concentration have also been documented. All these environmental trends point to an oligotrophication of the region and suggest that the spawning habitat of pelagic species such as anchovy (clearly dependent on river run-off waters) may be endangered in the coming decades (Palomera *et al.* 2007). The predicted increase in water temperatures, lower wind stress and precipitation and the consequently higher stratification have been reported to drive changes in the composition and phenology of planktonic communities and to increase the population size of jellyfish. Jellyfish blooms may negatively affect fish due to competition for food or through direct predation on their fish eggs and larvae (Tilves *et al.* 2016). Understanding the mechanisms relating environmental changes to the extent of spatial and temporal location of suitable fish spawning habitats is a key first step towards predicting and projecting such future changes and thereby adapting to them.

Future directions

In a context of global change, the research on early life history should address the consequences of climate forcing and other anthropogenic impacts, such as fishing exploitation, on fish eggs and larval survival. However, the effect of these drivers on the early life stages has received little attention, especially with regard to their particular habitat and physiological requirements. A thorough knowledge of fish larval ecology, fish distributions and spawning seasons and locations is essential to evaluate the impact of climate change and ecosystem shifts on the conservation of fish populations. This knowledge will be critical for future fisheries management.

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2.9. Charismatic, threatened and unknown: marine predators in the Anthropocene

Joan Giménez, Francisco Ramírez, Marta Coll, Joan Navarro

Marine mammals, seabirds and other marine predators such as sharks, tunas and swordfishes are charismatic species that people identify with. They have inspired award-winning documentaries and popular movies, as well as many books for children and coffee tables. They also attract millions of people to observe them in natural places all over the world, and some of them are considered important species for local and global fisheries and iconic food for some cultures. Unfortunately, many species of marine predators are decreasing in number and some are even threatened or extirpated from some marine areas. Overall, their poor conservation status and the low viability of their populations within the Anthropocene era are directly or indirectly linked to human-driven impacts, such as direct exploitation or mortality due to accidental capture (by-catch) during fishing, the impact of climate change, the depletion of their prey through the exploitation of marine resources and the loss or degradation of marine habitats.

Focal species for conservation

Marine predators have been traditionally used as focal species in marine conservation because they can be flagship, keystone, umbrella and indicator species (Figure 1). Generally, their protection can boost the conservation of the wider marine community on which they depend. They are also important because they are considered "canaries in the mineshaft" and can be used as sentinels of the marine environment they inhabit. They can act as an early warning of decreasing marine health and serve as biomonitors of ecosystem-scale changes, such as the presence of pollutants. In addition, they can be quantitative indicators of key ecosystem components and important supporting services, such as fish abundance or fish stock health. Indeed, population declines in these marine predators have typically presaged fisheries collapses (Velarde *et al.* 2019).

Figure 1. The importance of marine predators. The images of the chinstrap penguin (*Pygoscelis antarcticus*) and leopard seal (*Hydrurga leptonyx*) were provided by Joan Giménez and those of the common dolphin (*Delphinus delphis*), orca (*Orcinus orca*), northern gannet (*Morus bassanus*) and Cory's shearwater (*Calonectris borealis*) by CIRCE (*Conservación, Información, Estudio de Cetáceos*).

Gaps of knowledge

Despite the undeniable progress in our comprehension of these marine species, many of them are largely unknown, and considerable efforts are still required to promote their conservation and use as sentinel species through a better understanding of their biology, ecology, physiology and behaviour, in addition to the multiple threats and challenges they are facing (Figure 2). For example, few studies have analysed changes in their abundance, distribution, trophic ecology or movement. In part, this is because studying them presents considerable challenges, as marine predators are typically highly mobile animals that spend most of their time underwater and frequently use offshore waters (high seas beyond national jurisdiction) or transboundary areas on their long-distance movements. Filling the main gaps of knowledge and identifying the key biological and ecological aspects that may contribute to the conservation of these marine species throughout their annual cycles and distribution ranges therefore require local to transnational research initiatives, along with novel and interdisciplinary approaches.

For example, it is now possible to conduct multidisciplinary studies with approaches that range from analysing intrinsic biomarkers (e.g. stable isotope analyses in individuals' tissues) to tracking individuals' movements using biologging, acoustic or visual methods, which provide a more holistic understanding of the role of environmental and human factors in shaping the distribution of these species (Navarro *et al.* 2016). This information is also crucial for understanding how these long-lived marine organisms respond to environmental changes and other threatening human stressors. The integration of all this ecological and biological information in marine spatio-temporal ecosystem models allows us to identify the ecological role of marine predators (Coll *et al.* 2013) and to evaluate the effect of establishing marine protected areas (MPAs) to safeguard these species from extinction and reach relevant conservation targets (Giménez *et al.* 2020).

IIn order to rebuild marine life, reliable and knowledge-based conservation strategies should

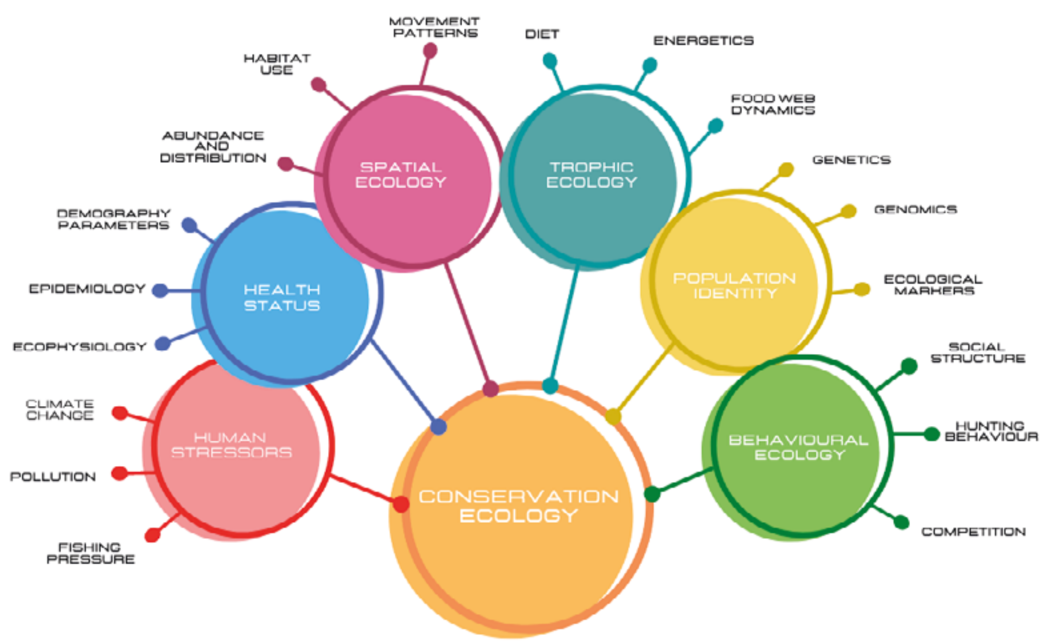

Figure 2. Precise understanding of different subfields is needed to inform proper conservation strategies to preserve and recover marine predator populations in the Anthropocene.

be implemented (Duarte *et al.* 2020). For instance, establishing reliable MPAs to safeguard and restore large marine predators to resilience levels of abundance can lead to the recovery of an ecosystem, potentially restoring biodiversity and ecological functioning. However, spatial-based approaches should be combined with threat-based approaches such as improving fishing selectivity and mitigation of ocean noise. that allow the management of cumulative impacts to reach safety levels. This involves the development of integrated marine and maritime spatial analyses and tools to analyse and manage the marine ecosystem in all its complexity.

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2.10. Ecological integrity of the seabed: trade-off between exploitation and conservation

Montserrat Demestre, Silvia de Juan, Alfredo Garcia-de-Vinuesa

Humans have obtained food from the sea since ancient times. Over time, humans have improved extracting methods by adapting fishing practices to the biology and behaviour of the target species. The species that live near the seabed, known as demersal and benthic species, are extracted with fishing gears that operate over the seabed. Some of these bottom-contact gears, like trawling nets, have a very low selectivity as they catch all the organisms on the trawling path. Other fishing gears, such as trammel nets or long lines, are more selective as they do not have direct contact with the seabed. A continuous and intense trawl fishing is one of the most pervasive impacts for benthic ecosystems, with a consequent degradation of the ecological integrity of the seabed; in other words, a loss of the Good Environmental Status of benthic habitats (de Juan *et al.* 2009). This effect is crucial as the ability of ecosystems to provide benefits to society tightly depends on its ecological integrity.

Fisheries by-catch: survival of discards

Trawling is a non-selective activity that catches commercial species (like hake, angler fish, Norwegian shrimps), but also non-commercial organisms (e.g. swimming crabs, starfish, benthic fish); this in known as accidental or unwanted catches (Figure 1). Most of the accidental catch is returned to the sea, dead or alive, which is known as discards. A fraction of the discards can be composed by commercial species that do not comply with the Minimum Landing Size and, therefore, cannot be commercialised (Garcia-de-Vinuesa *et al.* 2018). The mortality of the discard fraction is an additional direct effect of fishing activities that must be taken into account. Scientific studies evidence that the survival of discarded fish is very low, whereas the invertebrates might have higher survival rates (Demestre *et al.* 2018). A higher survival of invertebrates is driven by their external protection (e.g. crustaceans and gastropods), their regenerative capacity (e.g. starfish), or their living mode (e.g. the isolation mechanisms exhibited by bivalves).

To achieve a balance between the exploitation and the conservation of the marine environment, alternative fishing nets that minimise the by-catch have been designed. Experimental trawling nets include fishing nets of variable sizes, or exclusion devices in the net to allow the escape of accidental catches. By avoiding these

Figure 1. Image of a trawl catch on a crinoid bottom showing large numbers of *Leptometra phalangium*, an unwanted species. Fishing area on the coast of Blanes frequented by trawlers. CRIMA experimental fishing survey (RTI2018-095770-B-E00).

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unwanted catches, the biomass of marine resources increases in the mid to long term, which benefits the marine environmental and the fishermen revenues.

Trawl fishing has additional indirect effects over the seabed; society at large are often unaware of these effects. These indirect effects include a reduction of the biodiversity and a degradation and homogenisation of the habitats, with consequent shifts in benthic communities towards communities dominated by species that are resilient to trawling (de Juan and Demestre 2012). It is necessary and urgent to understand the resilience limits of benthic communities in order to avoid irreversible changes with important implications to the ecosystem functioning. The loss of key ecosystem functions might push towards the progressive loss of important services to society, such as fishing resources.

To minimise fishing impacts and contribute to maintain the resilience of marine communities in the long-term, different measures are currently in force in European fisheries, such as spatial and temporal bans or modifications in the trawling gear to minimise contact with the seabed (Demestre *et al.* 2008).

Emblematic benthic habitats in risk

These interventions are crucial in habitats identified as emblematic due to a high diversity and productivity. And this is the case for maerl beds and areas dominated by crinoids. These habitats are distributed along the Mediterranean coasts, overlapping areas with intense fishing activity.

Maerl beds are aggregations of free-living rodoliths, composed of red calcified algae, that have a key role in nature due to their capacity to store carbon and thus contribute to climate change mitigation. The rodoliths provide a three-dimensional habitat where numerous species seek refugia. Maerl beds are principally distributed between 30 and 70 metres in the Mediterranean, with preference for transparent areas with low sediment input (Figure 2A). Maerl beds, and some of its red calcifying algae (e.g. *Lithothamnion corallioides* and *Phymatolithon*

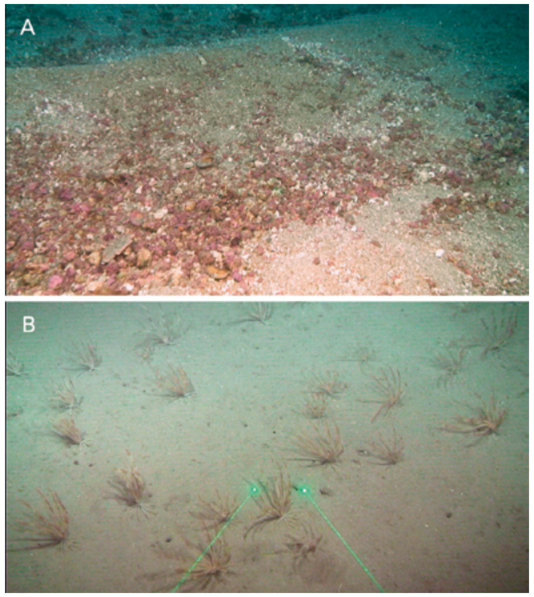

Figure 2. Image of a seabed: A, of maërl whith rhodolites along the valleys of the current ripple-marks, B, of crinoids (*Leptometra phalangium*) oriented towards the current to capture the suspended organic matter. Area near the Blanes coast frequented by trawlers. Oceanographic cruise CRIMA (RTI2018-095770-B-E00).

calcareum) are protected under the EU Habitats Directive. Despite this protection framework, trawl fishing is only forbidden at a regional scale bellow 50m depth and there is no consolidated protection framework for these habitats in the Mediterranean.

Crinoids beds are mainly composed by concentrations of *Leptometra phalangium* between 100 and 170 metres depth in the Mediterranean (Figure 2B). They have a preference for areas where surface waters are very rich in phytoplankton, which provides a large contribution of organic matter when it falls to the seabed. This organic matter reaching the seabed is consumed by many benthic organisms, including crinoids. These habitats have an important role in benthic ecosystems and provide habitat for numerous commercial species; in consequence, the EU has classified them as sensitive and essential habitats.

There is strong evidence of the impact of fishing activities on the Good Environmental Status of benthic habitats and the seabed, which compromises benthic ecosystem resilience and overall ecological integrity. Despite

The planetary organism
The impact of the Southern Ocean on climate
Life in the oceans
Microorganisms in a changing ocean
A microbial ocean with no boundaries
Proliferations of photosynthetic organisms
Symbiosis
Fish in the face of global change
Marine predators in the Anthropocene
Ecological integrity of the seabed
The changing colours of Antarctic marine life
Restoration of deep ecosystems on the Catalan margin
Fishermen and scientists
Looking with remote eyes
Renewable maritime transportation
Adapting beaches for the future

this, the current scenario is a trade-off between exploitation and conservation, with predominance of fishing exploitation. We need to reverse this trend and design management strategies that seek a balance between these two actions. It is worth to note that, according the EU directives, in 2023 the member states need to prove a significant advance towards the protection of 30% or their maritime territories. To advance in this direction, maerl beds and crinoids aggregations are priority candidates to effectively increase the protected area in our coasts and seas. The long-term conservation of the high biodiversity, and associated functions and services, provided by marine habitats depends on the management of this poorly known ecosystem that has been historically impacted by humans.

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2.11. The changing colours of Antarctic marine life

Enrique Isla, Julian Gutt

Ipsa scientia potestas est (knowledge itself is power), wrote Francis Bacon in his *Meditationes Sacrae* in 1597. Since then, mankind has acquired considerable knowledge, and power, but one of the most evident consequences of this process is the deterioration of the environment and of life on Earth. The current state of our ocean stimulated the United Nations to launch its Decade of Ocean Science for Sustainable Development (2021–2030), aiming to produce seven outcomes that will describe "the ocean we want" by the end of it. Among them, the second outcome, "A healthy and resilient ocean where marine ecosystems are understood, protected, restored and managed", is based precisely on what Francis Bacon, the father of the scientific method, proposed: the better the information we have, the more ability we will have to control events, or at least to project them.

Within this framework, the Antarctic is particularly important. It is perhaps the least known region of the planet, but it suffers comparable anthropogenic pressure to those of its counterparts at lower latitudes. This situation leaves us comparatively less time to improve our knowledge of the Antarctic before the ongoing anthropogenic environmental transformation drives its colourful marine ecosystems to a point of no return. Climate change is now perhaps the most important human threat for Antarctic ecosystems (Gutt *et al.* 2020).

Antarctica has been evolving in almost complete thermal isolation since approximately 30 million years ago, when the opening of the Tasmanian Gateway enabled the onset of the Antarctic Circumpolar Current and the establishment of the freezing temperatures that regulate life in the Southern Ocean. During this period, Antarctic life has thrived in unique environmental conditions, which are particularly constant near the seafloor. There, darkness and a fairly low temperature and salinity variation accompanied the benthic fauna into a state of high endemism, abundance and diversity of species and colour (Figure 1), which depends on the predominant white, green and blue at the sea surface.

From white to green: the ocean surface

Sea ice modulates marine life in the Antarctic. Antarctic sea ice can cover up to 20 million square kilometres during the winter and constitutes one of the largest biomes on Earth. It is a porous structure containing a network of brine channels full of microscopic life that is captured during the formation of the ice in the cold months of the year. When the spring arrives and melting starts, the sea ice microbiota finds nutrient-rich sea water, where it blooms and turns the white into green, generating sufficient food to maintain the entire Antarctic marine life.

From green to multicolour: the sea floor

Antarctic wind storms are common during the summer, and their action on the sea surface enhances biological production and particle aggregation, generating strong organic matter pulses to the sea floor (Isla *et al.* 2009). This summertime particle rain blankets the seabed with a green mat full of energy, which will fuel the multicoloured benthic life even during the

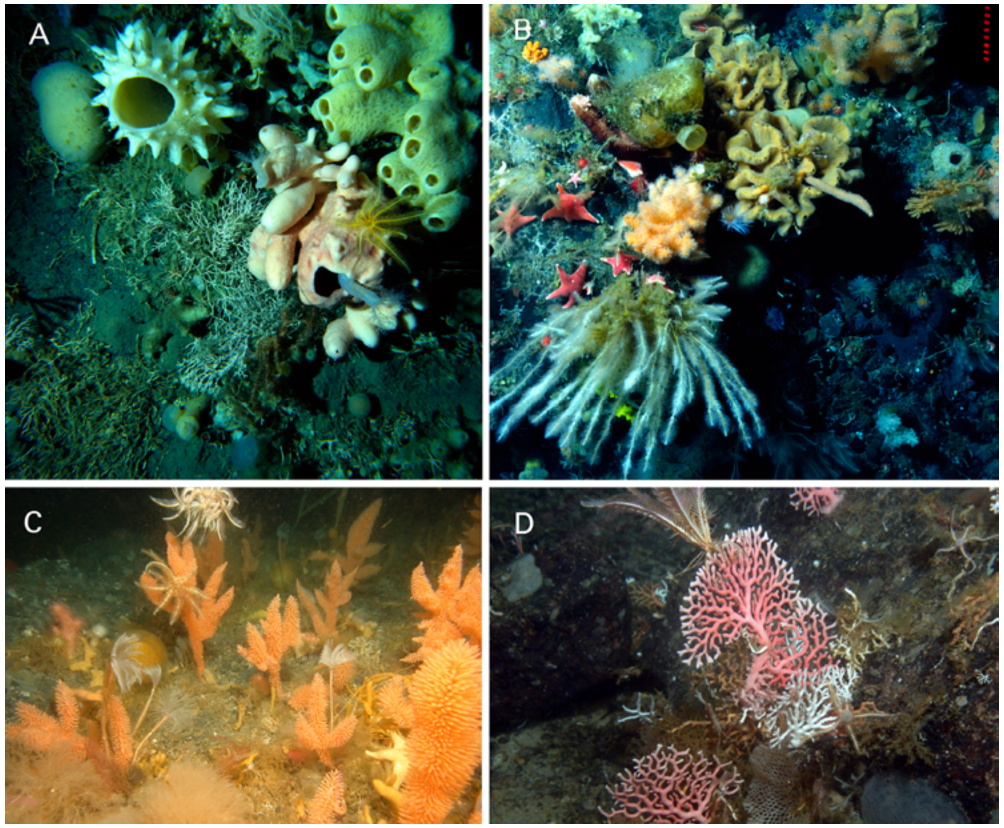

Figure 1. Benthic communities at the seabed of the Southern Ocean are rich in abundance, biomass, life forms and species. They comprise sponges, bryozoans, sea-cucumbers and compound ascidians (A). In addition, they are shaped by solitary ascidians, sea-stars, sea-fans and other soft corals (B). Orange can become the dominant colour in soft coral assemblages (C), and some filigrane hydrocorals that can occur in high abundances have a rare pink colour (D). The photograph area for figures A and B is approximately 1.5 m^2, and for figures C and D it is approximately 0.4 m^2 in the foreground.

dark winter months and also cover the few brownish patches of sediment not covered by benthic animals (Figure 2). However, there are thresholds, and if this summer energy surplus diminishes, it can leave benthic life starving.

Changing colour palettes

Warming in the western Antarctic Peninsula triggers several processes that modify marine colour patterns. The melting of glaciers introduces dissolved nutrients and mineral particles into the adjacent water column. Whereas at first glance the deep blue can turn into green due to flourishing algae nourished with glacier-derived nutrients, the sediment load eventually increases the turbidity and changes the green areas to milky turquoise and brown patches (Gutt *et al.* 2020). Pelagic organisms immersed in the brown clouds may clog their digestive tract and collapse, turning the dark mineral colour of the beaches into bright orange and red caused by landings of dead krill brought ashore by the wind (Fuentes *et al.* 2016). The multicoloured seabed changes too. The sediment loads can also cover the sea floor with a heavy brownish blanket, which suffocates the benthic fauna that feeds on suspended organic matter. It is predicted that the multicoloured assemblage may eventually come back, but at a still unknown pace (Gutt *et al.* 2020). By contrast, in the eastern Weddell Sea, sea ice cover increases resulted in drastic reductions of primary production and benthic faunal biomass and a shift from species that feed by filtering organic material from the water to species that take their food from the

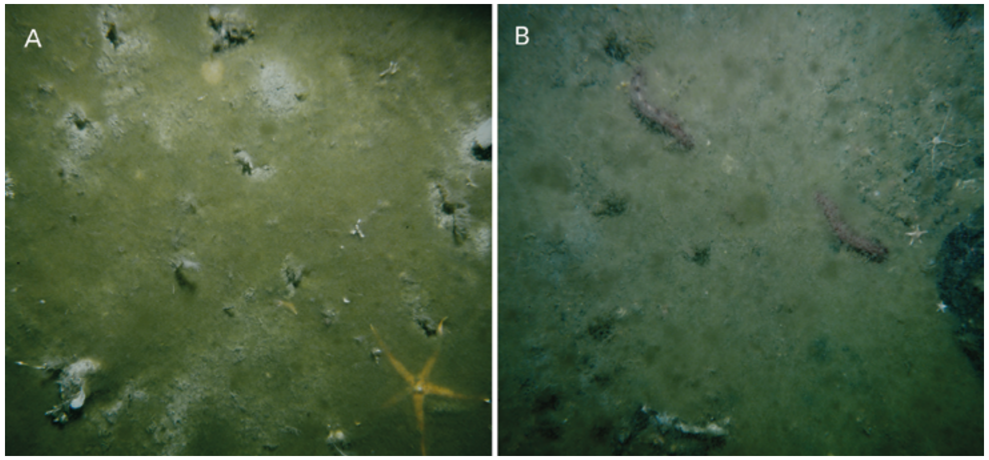

Figure 2. A sea-star (A) and the red-dotted holothurians (B) are almost totally sunk in a thick layer of green phytodetritus deposited after the convergence of a phytoplankton bloom and a wind storm. The photograph area for figures is approximately 1.5 m^2.

sediment surface –speaking in colours, changing green to white at the sea surface and reducing the multicoloured palette to brown on the seabed (Pineda-Metz *et al.* 2020). There, warming also contributes to these colour changes. The cold environment that shaped colourful benthic communities is now warming in spite of its location on the continental shelf at hundreds of metres of water depth. Warm water intrusions from the deeper continental slope expose life to water masses carrying the warm anthropogenic signature, with lethal consequences for organisms which lack the evolutionary ability to respond to large thermal variations (Isla and Gerdes 2019).

From black to white

The patterns and processes described above represent only a few luminous spots in the still dark and vast unknown universe of the Antarctic marine ecosystems. Ongoing scientific efforts are promising. International cooperation has been fundamental for Antarctic research and logistics, resulting in substantial advances towards a better understanding of the Antarctic marine environment and, given its strong contribution to global biodiversity and ecosystem services, of the global ocean too. However, time is running against these efforts, because global warming and pollution are rapidly transforming the environment before many biotic and abiotic processes are fully understood. Some species will be lost, the seascape will change, but other species will come and the seascape will be different: there will be winners and losers, yet the Antarctic colours will keep changing. Nevertheless, part of our natural library is burning and we must try to save as many books, and their colours, as possible because the key for understanding our ocean is there. More than four centuries after Bacon's reflection, the challenge for us now is to gain knowledge, and use its power to convert "the oceans we have" into "the oceans we want".

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2.12. Restoration of deep ecosystems on the Catalan margin

Jordi Grinyó, Maria Montseny, Patricia Baena, Stefano Ambroso, Andreu Santín, Marina Biel, Guillem Corbera, Janire Salazar, Josep-Maria Gili

Fishing is one of the human activities with the highest impact on seabeds. During the past hundred years it has gradually expanded to deeper waters, and almost all continental shelf and slopes worldwide have now been fished to some extent. In EU managed fishing grounds between 200 and 1000 m depth, it is estimated that bottom trawling has impacted between 2% and 77% of the total area (Eigaard *et al.* 2017). This has caused a substantial degradation of vulnerable marine ecosystems, which are generally formed by long-lived, slow growing, sessile (attached to the seafloor) structuring organisms. Among these ecosystems, we encounter sponge grounds, coral gardens and cold-water coral reefs that provide habitat to a wide range of associated species, several of which are targeted by fishing fleets. In addition, the ecological effects of bottom trawling on these ecosystems is extremely long-lasting, as no sign of recovery has been observed in areas closed to trawling for more than ten years (Clark *et al.* 2019).

The vulnerability and low resilience of these deep ecosystems and the need to preserve the provisioning services they deliver as they act as a habitat, nursery and feeding grounds for species of economic importance have led to the implementation of management measures such as the restriction of bottom contact gears and the establishment of marine protected areas on the continental shelf, slopes and seamounts. Conservation measures are crucial for the preservation and ecological recovery of natural and cultural heritage, but, given the current scale of environmental degradation across deep-water marine ecosystems, protection alone may now be insufficient. Instead, Earth's habitats are currently in need for active conservation and restoration measures that would help these ecosystems recover in terms of both biodiversity and ecosystem services.

Marine restoration: a rising phenomenon at a worldwide scale

Since the late 1980s, coinciding with the birth of the Society for Ecological Restoration, the practice of ecological restoration as part of a larger set of ecosystem management practices designed to conserve native ecosystems has received increasing global attention. Furthermore, the United Nations General Assembly has proclaimed 2021–2030 as the Decade on Ecosystem Restoration, following a proposal for action by over 70 countries worldwide (Waltham *et al.* 2020). Although during the last 20 years the restoration of marine ecosystems has increased substantially worldwide, most restoration actions to date have been carried out in shallow environments, mainly focusing on structuring species such as oysters, mangroves, seagrass, algae, temperate gorgonian assemblages and tropical coral reefs, which play a paramount role in the formation of a habitat. Globally, only seven active restoration actions consisting in the transplantation of nubbins of several cold-water coral species (e.g. *Oculina varicose* and *Desmophyllum perstusum*) and gorgonian species (e.g. *Paragorgia arborea, Viminella flagellum* and *Callogorgia verticillata*) have been performed in intermediate (50–200 m depth) and deep-sea (>200 m depth) envi-

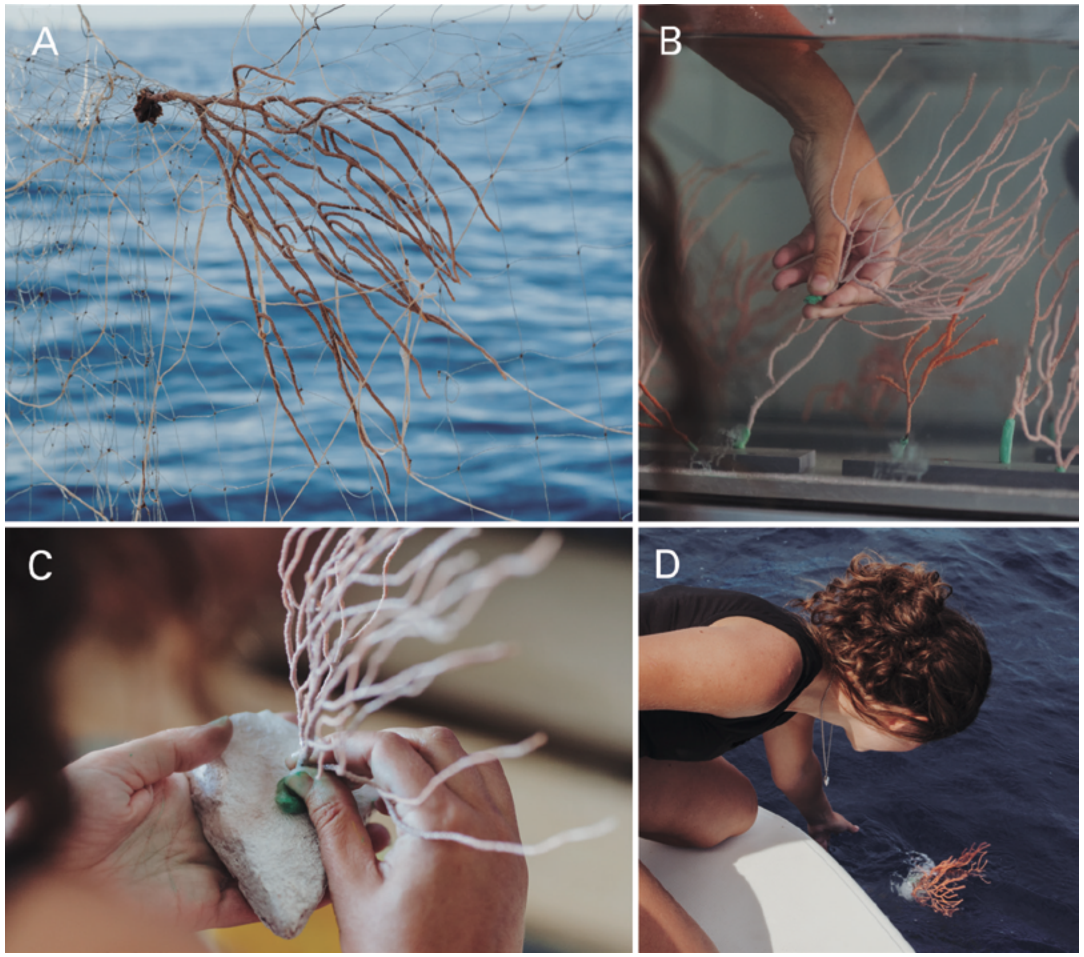

Figure 1. Sequential steps of the "badminton method". A, recovery of an *E. cavolini* colony entangled in a trammel net; B, maintenance of *E. cavolini* nubbins on aquaria; C, reattachment of *E. cavolini* nubbins to cobbles; D, tossing of restored *E. cavolini* nubbins to the sea. Pictures by Laia Sabaté.

ronments (Montseny *et al.* 2020). Owing to technical and logistic challenges and the high costs associated with working in deep-sea environments, these actions have been generally carried out over short periods of time (1 to 4 years) and covering small areas (2–20 m^2).

The marine ecosystems of the Cap de Creus: a lab for the development of innovative restoration methodologies

To overcome these limitations, in 2018, the team of Ecology and Resilience of Benthic Ecosystems in a Changing Ocean of the Institut de Ciències del Mar developed a novel cost-efficient restoration technique for cold-water coral gardens named the "badminton method" (Figure 1). This technique consists of attaching accidently caught sessile structuring organisms (e.g. gorgonians, sponges and soft corals) to cobble supports and returning them to deep environments by gently tossing the transplanted organisms directly from a boat (Montseny *et al.* 2020). Since 2018, this method has led to the restoration of 1688 colonies of the gorgonian *Eunicella cavolini* in a continental shelf environment (80–90 m depth), with a 90% survival rate one year after transplantation. Currently, this methodology is also being tested to recover populations of other sessile organisms commonly impacted by artisanal fishing fleets in the Cap de Creus, such as the soft coral *Alcyonium palmatum* and the large sponge *Axinel-*

la polipoides. The success of this cost-effective active restoration technique highlights the viability of large-scale restoration of impacted structuring organism populations, with promising results for the conservation and recovery of intermediate and deep-sea ecosystems. Indeed, in the near future, this restoration approach is planned to be expanded to several no-take zones (areas where fishing practice is permanently banned) on the Catalan shelf and slope in order to revert the poor conservation status of their benthic habitats, which were impacted by fishing activities during most of the 20th century. These restoration efforts would help re-establish ecosystem services such as nursery grounds and breeding habitats for other associated species (e.g. fish and decapods).

Overall, after being effectively restored, these areas could act as source habitats, promoting spillover of certain species to the adjacent fishing grounds, increasing the biodiversity of the Catalan continental shelf and potentially helping to maintain the long-term viability of its fisheries.

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2.13. Fishermen and scientists: synergies for the exploration, conservation and sustainability of the marine environment

Andreu Santín, Jordi Grinyó, Stefano Ambroso, Patricia Baena, Marina Biel, Guillem Corbera, Janire Salazar, Maria Montseny, Josep-Maria Gili

During the 20th and 21st centuries, the growing demand for marine resources by Mediterranean countries has led to a gradual increase in fishing pressure. As a result, both coastal and continental Mediterranean waters have suffered from the impacts of trawling and, to a lesser extent, of artisanal fishing with longlines, trammel nets and other minor fishing gear (Grinyó *et al.* 2022, Demestre *et al.* 2022). Following the indications proposed by the European Marine Strategy, a set of particularly vulnerable areas has begun to be delimited, and protection measures are to be implemented for their conservation (Law 41/2010, of 29 December, on marine protection; https://www.boe.es/eli/s/l/2010/12/29/41). These areas seek to develop integrated policies to promote sustainable fishing practices that prevent the over-exploitation of natural resources while at the same time mitigating the impacts that may occur on benthic habitats, which are those found directly on the seafloor. Although fisher's gilds are still operative in most marine protected areas, only a minority of scientific studies and management plans have integrated the experience and knowledge of fishers in such areas. This scant involvement of fishers in drawing up the management measures often results in their opposition to them, as well as a lack of motivation regarding proposals for a more sustaniable explotation and preservation of the marine environment.

First experiences: the artisanal fisheries of the Menorca Channel

In this regard, the research group on Ecology and Resilience of Benthic Ecosystems in a Changing Ocean of the Institut de Ciències del Mar has been working for years to achieve greater involvement and integration of fishers in scientific projects and management activities. As an example, during the exploration of the Menorca Channel, artisanal fishers in the area helped identify areas of high diversity on the limit of the continental platform, which have been unexplored so far but have been known for decades by the fishers. These areas contain dense communities of sponges and gorgonians, sometimes extending for kilometres, which could be listed among the best preserved in the northwestern Mediterranean (Grinyó *et al.* 2018, Santín *et al.* 2018), and which harbour several new species to science. In the Channel, specimens of various species of gorgonians (colonial organisms related to corals and without commercial interest) often get entangled in small-scale fishing nets and are systematically returned to the sea by the fishers. The colonies that are accidentally caught include some that are completely removed from their substrate and some that are still fixed to pebbles. Following a joint investigation with the fishers, it was noted that the survival of the ones attached to pebbles is much higher when they are returned to the sea. Therefore, on the basis of the knowledge acquired by these Minorcan fishers, we devel-

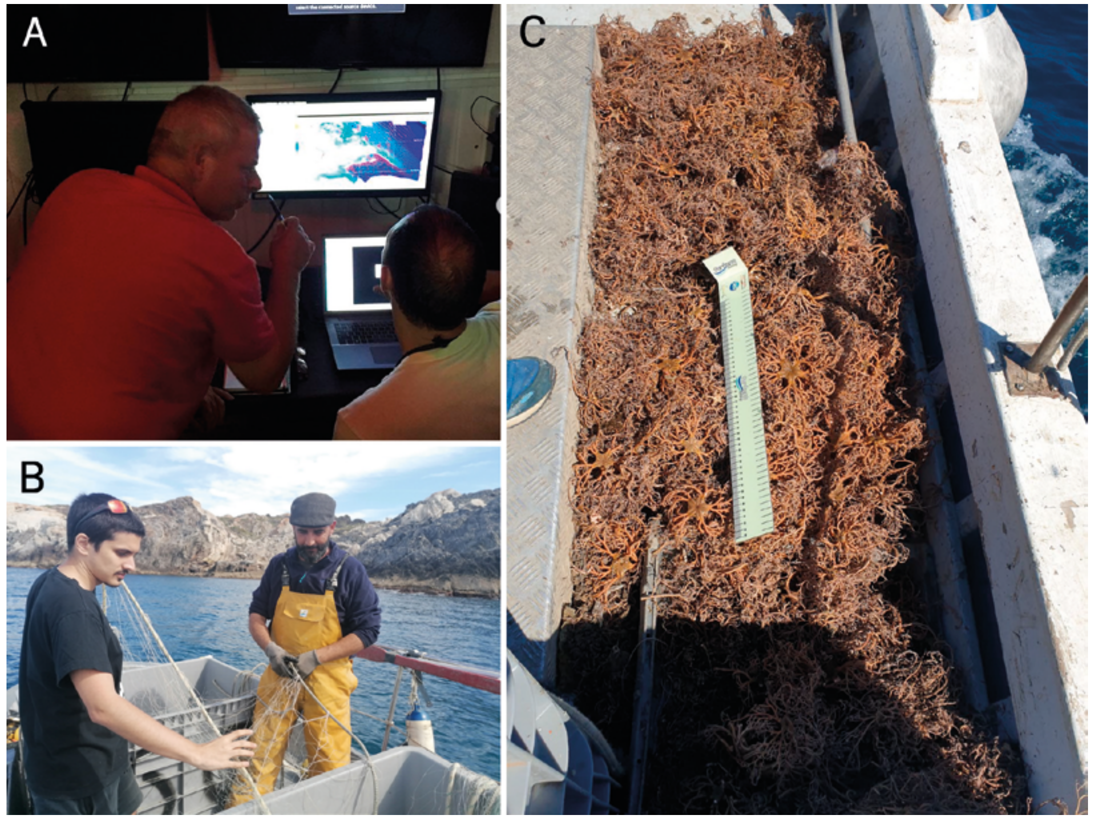

Figure 1. A, advice by artisanal fisherman from Port de la Selva to the scientific team of the MITICAP project during the exploration of the artisanal fishing grounds of the Cap de Creus by means of a remotely operated vehicle. B, collaboration between artisanal fishermen and scientists in the preparation of experimental artisanal trammel nets on board a fishing boat. C, hundreds of *Astrospartus mediterraneanus* specimens accidentally caught by artisan trammel nets in a single fishing event.

oped a method for restoring gorgonians that has been successfully applied for years in the Cap de Creus area (Grinyó *et al.* 2022, Montseny *et al.* 2021).

Nowadays: Towards a co-management model and conservation of marine resources

It is precisely in the area of the Cap de Creus (the first maritime-terrestrial national park in the Spanish state, recently included in the Natura 2000 Network) that the research group's efforts are currently focused. During the course of the Life+ INDEMARES project, it was found that, in the Cap de Creus marine area, as in the Menorca Channel, the best preserved areas were those inaccessible to trawling and only frequented by artisanal fishing boats (Gili *et al.* 2011). However, although the impact of small-scale fishing on the environment is lower, it still exists. Therefore, a close cooperation was initiated with artisanal fishers of Port de la Selva and Cadaqués with the aim of better understanding their techniques, promoting this type of fishing against more destructive ones and mitigating the impacts that it has in the area (Figure 1A). This mitigation has so far consisted in the modification of the fished areas, the selection of different fishing gear based on the habitats that each fishing area hosts, and measures to reduce ghost fishing (capture of marine organisms by lost and/or derelict fishing gear; Figure 1B). The fishers of this area accidentally catch species of high scientific interest, and they have helped to detect for the first time the presence of the gorgonian *Spini-*

muricea klavereni on the Catalan coasts (Yokeş *et al.* 2018). Another important contribution by the fishers was the detection of an increase in the population of *Astrospartus mediterraneus* (an emblematic ophiuroid of the Mediterranean region considered rather rare or scarce) that had gone unnoticed by the scientific community (Figure 1C). The significant increase in populations of this echinoderm has had a negative effect on artisanal fisheries, resulting in a considerable increase in net clearance times. However, communication between fishers and scientists enabled the problem to be analysed from an ecological point of view, helping to increase the confidence of fishers and their willingness to work along instead of with scientific staff.

The scientific community is making great efforts to bring science closer to society. In order to reverse the unsustainable extractive fishing model that prevails in today's society, all stakeholers need to be involved. Therefore, creating a model of close cooperation between scientific staff and fishers is essential in order to achieve a paradigm shift in the exploitation of fish stocks that will lead to more sustainable practices and allow artisanal fisheries to be supported and enhanced.

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2.14. Looking with remote eyes: novel technologies for a better management of the ocean

Francisco Ramírez, Isabel Afán, Nixon Bahamon, Marta Coll, Joan Giménez, Joan Navarro, Jeroen Steenbeek

The oceans cover about 71% of the Earth's surface and contain about 97% of the living space on the planet and somewhere between 500000 and 10 million different species. Oceans provide humans with natural benefits such as seafood provisioning, carbon storage and climate regulation –the so-called ecosystems services. However, despite their paramount importance for the maintenance of life and human wellbeing, oceanic systems are among the most complex, poorly understood and impacted biomes.

Oceans serve as a sink for excess CO_2 and heat from the atmosphere, with far-reaching consequences for weather patterns, marine productivity, marine food webs and food security. Concurrently, human fisheries are placing a severe burden on marine ecosystems, with approximately 94% of fish stocks worldwide being exploited at unsustainable levels according to the Food and Agriculture Organization (FAO 2020). The combined effect of climate change and overfishing can compromise the resilience of marine communities, making them increasingly vulnerable to these changes and to other anthropogenic impacts such as pollution and the degradation of marine habitats.

Monitoring climate and human-driven deleterious impacts on marine ecosystems is key to informing effective socio-political strategies needed to contribute to marine conservation and establish a necessary shift to a sustainable use of living resources. Climate and human pressures on the oceans are heterogeneously distributed, as are marine organisms (Ramírez *et al.* 2017; Figure 1), often hampering effective monitoring of impacts and ecosystem services.

How can we track and measure these impacts and assess them in the complex, remote and vast oceans?

Fortunately, the recent rapid advances in various observational and monitoring technologies have revolutionized the way we monitor the Earth, track human pressures and observe organisms in the wild. Information on key environmental and biological features can now be obtained at high spatial and temporal resolution through arrays of sensors globally distributed in space, in the air, on land and in water. Remote observing systems are particularly helpful as they can monitor the world's oceans, human activities and marine organisms, from coastal zones to remote areas where traditional observation is difficult. Furthermore, they provide information on human-driven environmental changes and allow monitoring the movements of marine organisms through animal-attached autonomous devices.

Ecological and environmental applications that use this information include long-term monitoring of key environmental variables, the identification of key marine areas that are highly impacted by climate and human-driven environmental changes and, importantly, the evaluation of animals' responses to these climate and human pressures. For example, the use of

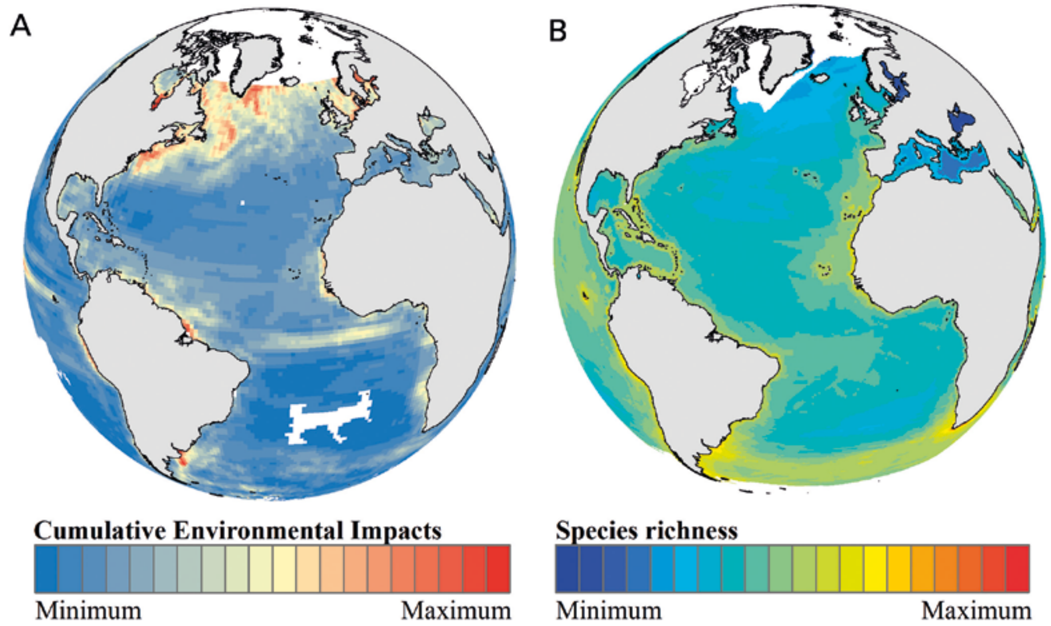

Figure 1. Climate-driven environmental changes are heterogeneously distributed spatially, as are marine organisms. Here, we identify marine areas that are highly impacted by equally weighted changes in sea surface temperature, chlorophyll *a* concentrations and ocean currents (A); and marine biodiversity hotspots on the basis of the spatially explicit information on the equally weighted distribution of fish (1729), marine mammal (124) and seabird (330) species (B). Data provided by IUCN (www.iucnredlist.org/) and BirdLife International (www.birdlife.org). Figures modified from Ramírez *et al.* (2017).

satellite radar and remote sensing imagery on artificial night-lights, especially when complimented with modelling techniques based on automatic identification systems or vessel monitoring systems, is currently providing the most reliable insights into the spatial distribution of human fisheries (including illegal, unreported and unregulated fisheries), shipping traffic and other human facilities/activities that potentially impact marine wildlife.

Other uses of satellite remote sensing imaginary and in situ observations from global networks of free-drifting buoys or oceanographic surveys include their integration into physical and biogeochemical models. These models constitute a promising approach to monitoring surface and sub-surface marine systems in near-real space and time, helping us to evaluate climate-driven environmental impacts, understand ocean-atmosphere interactions and improve ocean and climate forecasting when interlinked with models that represent more complex components of marine life.

There have also been huge advances in the way scientists track and monitor living organisms in the wild, along with the environment they inhabit, through animal-attached autonomous recording tags (or *bio-logging* devices, Ropert-Coudert and Wilson 2005). These devices include acoustic transmitters, miniaturized GPSs, cameras and multi-parametric sensors, which allow scientists to remotely obtain complex quantitative measurements of animals' natural behaviour in conjunction with the physical characteristics of their environment. This kind of information is providing the deepest insights to date on the biology, ecology and behaviour of species ranging from marine invertebrates to sharks, turtles, seabirds and large marine mammals (Figure 2). It also offers new capabilities for observing the ocean, the changing environmental conditions and their interactions with humans and, importantly, the consequences of these interactions on individuals and populations (Roquet *et al.* 2017).

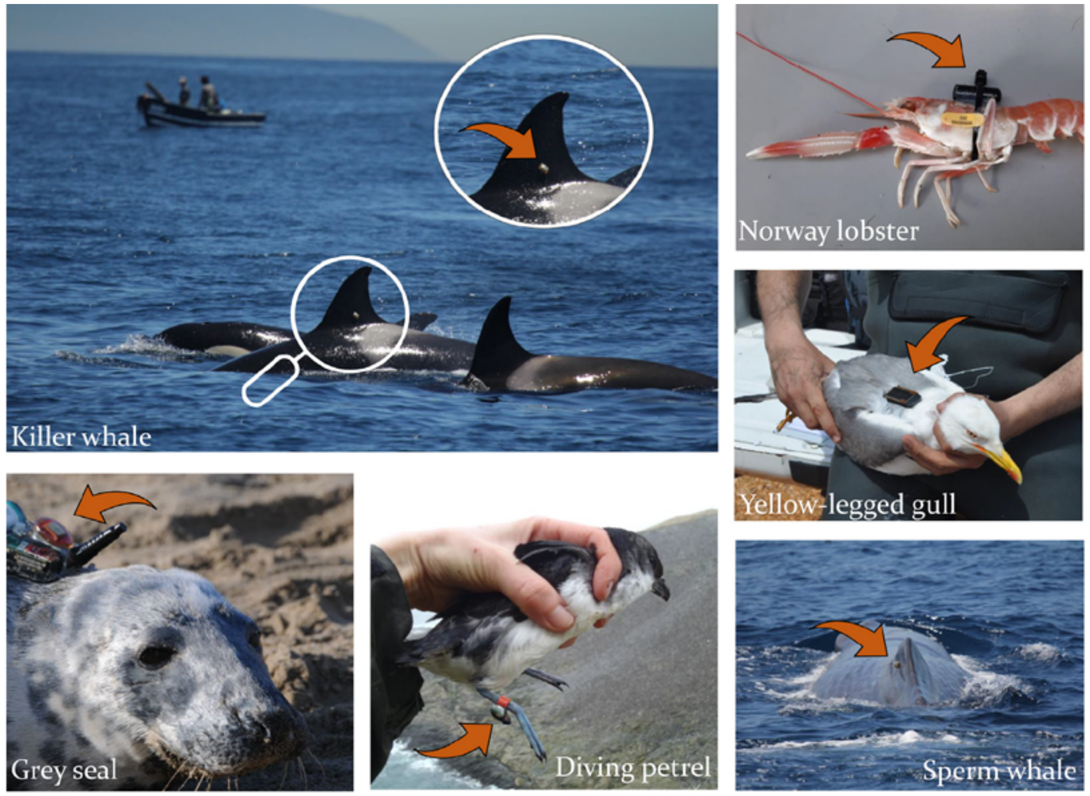

Figure 2. The recent rapid advances in animal-attached autonomous recording tags have revolutionized the way scientists track and monitor animals' natural behaviour, along with the physical characteristics of their environment. Here, we show a range of autonomous recording tags deployed in a wide range of species, from the small Norway lobster (*Nephrops norvegicus*) to the large sperm whale (*Physeter macrocephalus*). The images were provided by the authors, by CIRCE (Conservación, Información, Estudio de Cetáceos; killer whales and sperm whale) and by Mark Jessopp (University College Cork; grey Seal).

Towards a better management and conservation of marine systems.

Combining data from tagged animals with remote and in situ observations within numerical modelling frameworks has shown potential for identifying important marine areas (e.g. biodiversity hotspots) that (i) deserve conservation priority because they are impacted by climate and human pressures and (ii) can act as "climate refuges" because they are projected to be more resilient to climate change. Tagged animals can also help monitor the oceans' health, as they can integrate complex processes and trophic interactions into a low number of accessible signals related to behavioural responses, shifting distributions and changes in phenology or foraging strategies (Giménez *et al.* 2022).

Interestingly, from the smallest seabirds to the largest sharks and whales, most actively monitored marine animals are charismatic species that people can identify with (Giménez *et al.* 2022). This underpins the fact that the management and governance of marine habitats, species and resources does not only involve mediating between resource use conflicts and establishing marine protected areas; it also profoundly involves people's ability to connect with the species that somehow stand out (Simaika and Samways 2010). Accordingly, these species have the potential to act as "ambassadors", playing a vital role in education to help explain environmental issues to the general public and thus involve citizens and management authorities in the conservation and protection of the marine environment. By protecting these species, we can also protect their habitats and, indirectly, other species that live in their ecological communities, along with important provisioning services.

Overall, new remote sensing and bio-logging technologies are providing us with new eyes with which to observe the oceans. However, a challenge we face is how to make best use of this information to overcome some of the major conservation challenges ahead.

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2.15. Towards a renewable shipping for a resilient and healthy ocean

Jordi Solé, Antonio García-Olivares

Maritime transport is one of the most polluting modes of transport, not only in terms of its greenhouse gas emissions but also because of the high pollution it generates compared with other modes. In addition, maritime transport has other impacts such as collisions with mammals, pollution by oil or fuel leaks, dumping of bilge water and pollution of port waters by ballast water. Emissions from shipping are estimated to be 2.2% of the total emissions caused by human activity in 2012 and are projected to increase by 50% to 250% if no action is taken (Rahim *et al.* 2016). On the other hand, maritime transport is key in the global economy because it accounts for between 80% and 90% of world trade (Balcombe *et al.* 2019).

Evaluating the marine transport impacts

Given the impacts that maritime transport has on the environment, it is necessary to make a transition to a model based on renewable energy. A renewable economy needs a global transformation of transport which, in turn, needs structural changes in the logistics of the sector. We must evaluate the implications and the cost of this change. We must take into account geophysical indicators (such as the available reserves of material or energy sources), the limitation of minerals (batteries, wiring, motors, etc.) and the re-design of transport networks. In this article, we take as a reference two studies (García-Olivares *et al.* 2018, 2020) that were carried out in the framework of the MEDEAS (www.medeas.eu) project, in which a simulation model was developed to explore the future alternatives for designing a low-emission, renewable energy-based socio-economy and assess the costs of replacing the existing fleet in 2016 if we change all existing ships for ones with non-fossil technology.

Some estimates

The methodology we use evaluates these costs through energy intensity (https://en.wikipedia.org/wiki/Energy_intensity). The energy intensity of an economic sector is the energy used to generate a unit of GDP, so what it gives us is energy (joules) per dollar (or euro). With the energy intensity and the estimated cost of the new ships, we get an energy cost (in joules) to transform the entire fleet. The (energy) cost assessed here focuses on replacing each mode of transportation with renewable alternatives and does not take into account several factors that should be considered in a more detailed analysis. It is therefore intended as a basic exercise to show that the currently proposed investments are totally insufficient and serve as a warning to shipping companies in the future: if we assume the possibility of replacement and calculate the full cost, we must add to this cost the electricity generation, energy infrastructure, maintenance, etc., all in a present/future with less power available because of the decrease in fossil fuel production.

In the case of the total maritime fleet, we must deduct the current oil tankers (because in an economy without the need for fossil resources, they would no longer be necessary) and make the calculations on the basis of the other merchant and passenger ships. With this

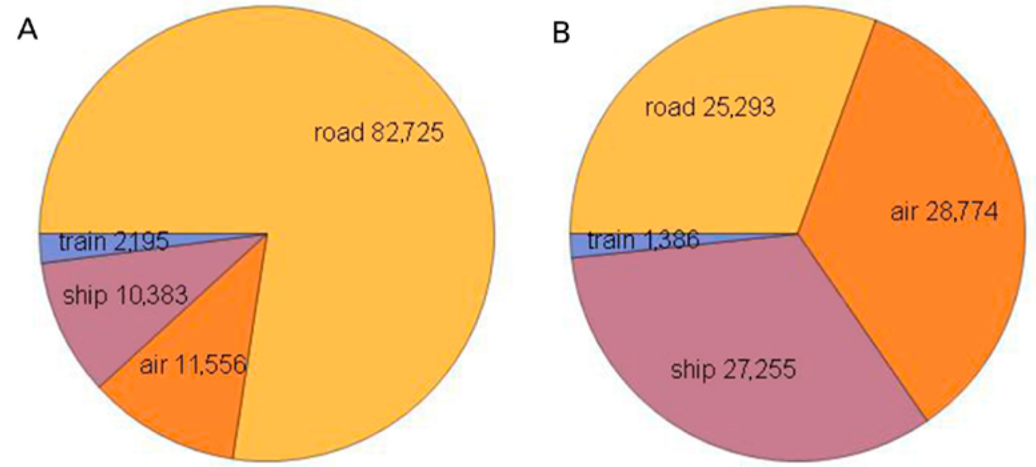

Figure 1. Proportion and energy (in PJ) required for each mode of transport: A, current situation; B, after the renewable transition. As seen, renewable transport will require less total energy, and maritime transport in particular grows in its energy requirements despite being halved.

in mind, replacing the current fleet with a renewable one results in a 163% increase in the energy consumption of maritime transport. This increase is due to the fact that, with current technologies, it is impossible to electrify the fleet. It would have to continue using combustion systems, but fuelled by natural gas. This would involve sharp price increases and declining intercontinental transportation, which may result in a relocation of economic activity. Therefore, apart from the use of fuel cells and methane, it is necessary to reorganize and reduce maritime transit, because the transport of goods is currently one of the largest consumers of fossil fuels and, as stated above, it is very polluting for both air and water. Given the current lack of port infrastructure to store methane or hydrogen, in the coming decades greater use of biofuels may be needed to mitigate the carbon footprint in line with recommendations of the International Panel on Climate Change. In a 100% renewable economy, building such an infrastructure and using methane or hydrogen would be a more economical option and would save a significant amount of energy. However, if current technologies allow us to achieve less energy loss, we would be able to avoid the massive use of biofuels. Therefore, as a hypothesis, we assume that methane would be the main fuel for the marine fleet in the future. (It should be added that reducing the speed of maritime freight transport would lead to significant energy savings.) Maintaining the same services as in 2016, the transition from maritime transport would require 2.9% of the total embedded energy to make the entire transition to renewable transport. Figure 1 shows the proportion and amount of energy (in petajoules, PJ) required for the current transport (Figure 1A) and that which would be required after the renewable transition (Figure 1b).

Shortly...

If we focus only on the EU, the energy cost of the maritime transport transition would be 3.5% of the total energy used for changing all modes of transport in EU. The total energy consumed in 2016 was 106,859 PJ, whereas in an approximately equivalent but renewable sector, it would be 82,708 PJ, approximately 23% less, thanks to the savings in road transport. But the high energy consumption of ships and aircraft in a renewable economy would push for a reduction in the intensity of these modes of transport, by about 50%. Thus, the 23% of reduction of all the transport modes needs to be framed within a reduction and transformation of modes of transport, so although it may seem small, it implies a reduction of half of the current fleet. This transformation of transport must be accompanied not only by a transition of all modes but also by profound socio-economic changes. We need to move to an economy that overcomes the need for indefinite growth, given an immediate future with serious problems of access to material resources and an environment with growing threats of pollution, ecosystem conservation and climate change.

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2.16. Adapting beaches for the future

Jorge Guillén, Ruth Durán, Gonzalo Simarro

The Spanish Mediterranean coastline has a total length of approximately 3000 km (including islands) and is characterized by a great geomorphological diversity, including more than 750 km of sandy beaches. The current configuration and problems of the coastal system can be explained mainly by human intervention in the natural environment, which has intensified since the middle of the 20th century with the regulation of hydrographic basins, the demographic explosion and massive tourism in the coastal zone. The consequences of this transformation on the physical coastal environment have been the decrease in sediment input from rivers to the marine environment, changes in the redistribution of sediment and the urban occupation of a large part of the emerged beach. These human-induced changes have led to a considerable increase in risks (erosion and flooding) on the coast over the last few decades and a continuous loss of the emerged beach surface, which in turn has resulted in a large increase in the need for coastal protection works. Superimposed on these processes, variations linked to climate change (including water temperature, sea level, storms and flash floods) are becoming more important for the coastal ecosystem and will increase the risks in the coastal zone and produce generalized beach erosion in the near future (in fact, they are already doing so). On a global scale, it has been estimated that more than 50% of current beaches will disappear by the year 2100 as a consequence of sea level rise (Vousdoukas *et al.* 2020).

Shoreline change and monitoring

There is therefore evidence that in a relatively short period of time (a few decades) the coastline as we know it today will change, so there is necessary to design a new coastline that can adapt to the expected changes following guidelines that society can accept. Without discarding any of the possible options in the adaptation strategies, it seems reasonable to promote those that include nature-based solutions, as they prioritize the sustainability of the marine ecosystem and will presumably have a lower cost for future generations. This long-term strategy must be multidisciplinary and cross-cutting, considering all environmental aspects that can be incorporated together with social and urban planning aspects. To achieve this, it is necessary to obtain continuous, high-quality data on parameters of interest (for example, the morphological evolution of the beaches and the frequency and intensity of storms.) and, more importantly, to process these data to provide an updated view of the state of the coast at all times.

The Oceanic and Coastal Sedimentary Processes Group of the Institut de Ciències del Mar-CSIC in Barcelona began its studies on the sedimentary dynamics of the Catalan coast and the distribution of sediment inputs to the marine environment in the 1980s. New observational methodologies have been progressively incorporated in these studies, such as video monitoring of the coastal zone (Figure 1), the use of tripods on the seabed, instrumented anchorages for data collection (current velocity and suspended sediment concentration) and the incorporation of citizen science (the CoastSnap project). The Group's experience in data collection and, above all, in data interpretation and definition and in cataloguing parameters of interest (Durán *et al.* 2016), allows us to offer to the society a consolidated scientific knowledge for the evaluation of impacts and the prediction of the future behaviour of coastal ecosystems.

Figure 1. Beaches of Barcelona (left) and Castelldefels (right) one week before (top), during (centre) and one week after (bottom) the Gloria storm of January 2020. This storm was the most extreme ever recorded on the Catalan coast. Images taken from the ICM-CSIC video monitoring stations (coo.icm.csic.es).

The general objective of the coastal adaptation strategy is to assess whether it is feasible to maintain (or even improve) the functionality of beaches as a protection from storms, an habitat and a place for social uses in the long term, and to propose the main lines of action to achieve this. These lines of action should consider a more sustainable future in relation to the use of beaches, which includes, for example, reducing the need for sand for artificial regeneration and minimising the negative impacts of storms; improving the quality of water and sediment; and minimizing maintenance costs. And this must be done in a scenario where the needs of almost all the beaches will be in mutual competition, so that a general coordination (including a comprehensive sediment management plan) will be necessary to optimize the available resources. In short, this adaptation of the beaches, which will have to be faced over the coming decades, requires a considerable economic investment and may entail the need to give up certain beaches. It must be attempted to avoid further compromising future generations so that recreational access to the beach will not become a luxury.

Identifying adaptation strategies

In order to build a more sustainable alternative, two complementary lines of action are suggested in the short term: a) improving and adding versatile and scalable protection structures that can be easily expanded according to the needs of the beaches where they are essential (dune fields, artificial regeneration, protection dikes, etc.); and b) promoting "smart beach" actions that consist of optimizing management based on detailed knowledge of available resources, proposing measures to reduce damage from storms, optimize the use of sand and anticipate future problems. The use of observation tools such as video monitoring has proved to be very useful in beach management (Simarro *et al.* 2020) and has been successfully applied over the last two decades in the city of Barcelona (Ojeda and Guillén 2008).

In the longer term, what will happen if extreme storms such as the one that occurred in January 2020 (the Gloria storm) come to occur every two to three years, as forecasts for the mid-21st century indicate? It will be difficult to maintain the same configuration of beaches as at present: the flood level will rise and the destructive impacts of waves will affect hitherto protected areas. On a time-scale of decades, an urban and land management policy must be initiated to expand the maritime-terrestrial zone and incorporate an interior zone with sufficient extension to allow the beach to accommodate erosion and flooding during high-energy events (artificial dunes that facilitate adaptation and protection, areas capable of absorbing floods, etc.). The more natural a beach is, the more easily it can adapt to new conditions. When gaining space for the beach is not a possible alternative (as in many urban beaches), the development of new protective structures and large-scale artificial sand reclamation can be considered.

In summary, humankind has been able to enjoy contact with the sea in many different ways and has adapted very quickly to the changes that have occurred throughout history. Our adaptation to different uses is much easier than the geomorphological adaptation of the coast itself. Therefore, maintaining the recreational aspects of the beach should not be our essential objective in the design of our beaches of the future; rather, it seems more appropriate to prioritize moving towards a safe, environmentally healthy and sustainable coast.

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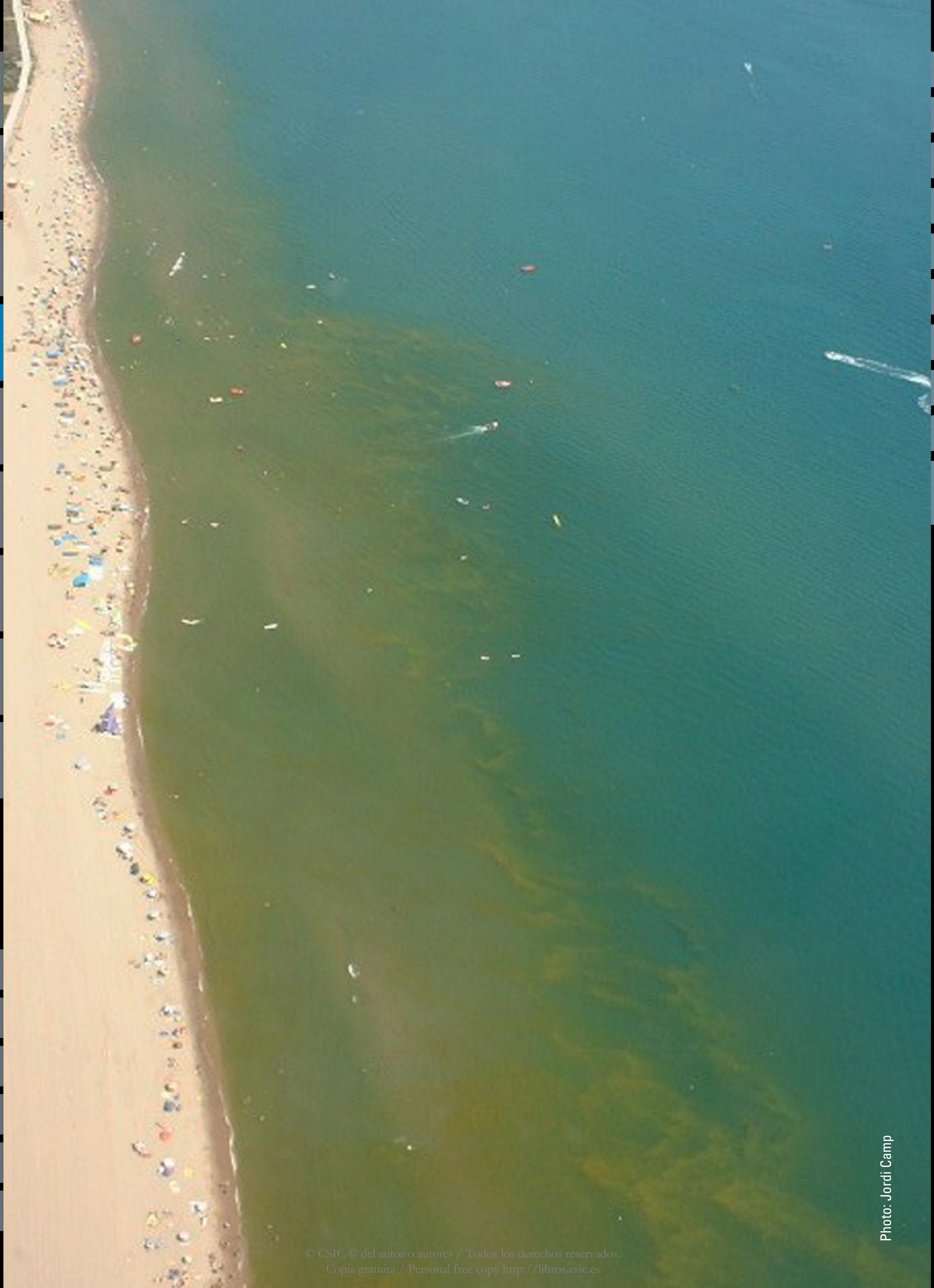

Photo: Jordi Camp

3. Productive ocean

Mercedes Blázquez, Laura Arin, Blanca Figuerola

Oceans are an important source of food for Humanity. Oceanic production depends on primary producers, mainly phytoplankton, which are photosynthetic organisms that transform inorganic matter into organic matter and oxygen using the sunlight. These organisms are the basis of oceanic food webs and become the main source of all exploitable marine resources. The proper use of these resources by Humankind is not only based on their sustainable exploitation, but also on a fine-tuned balance among all the ecosystem components. To this end, it is essential to have an integrated knowledge of the dynamics of the oceans and of their inhabiting living organisms (Figure 1).

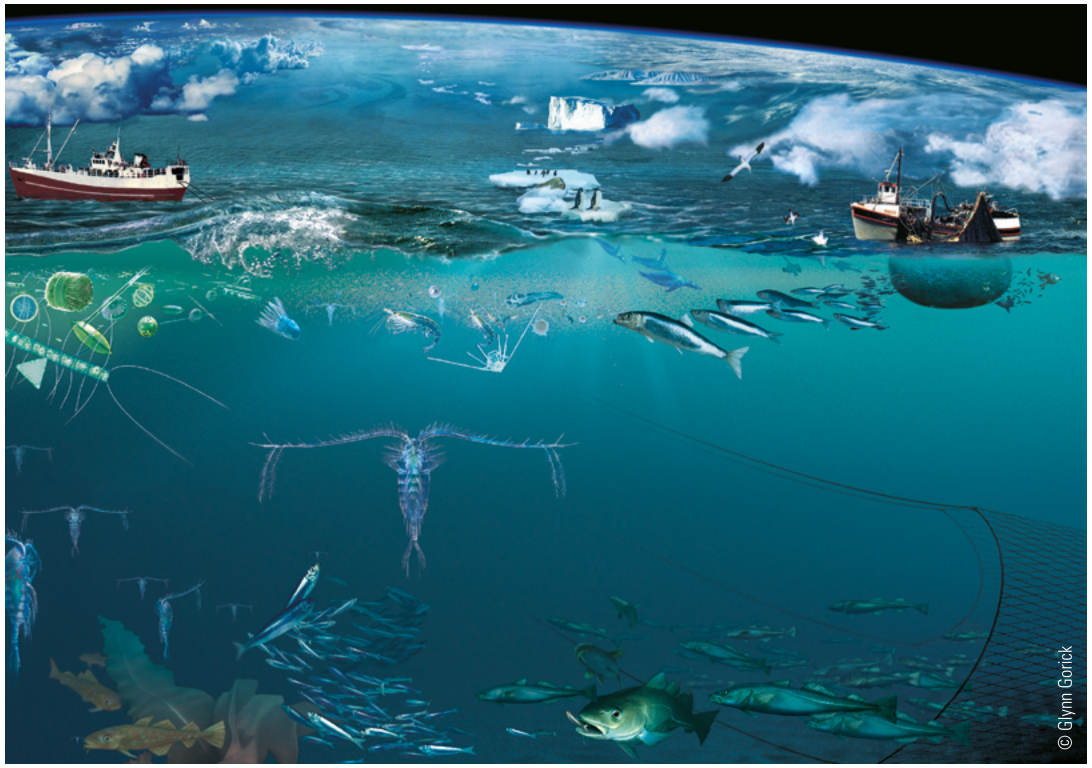

Figure 1. Some key components of oceanic food webs that are essential for obtaining exploitable marine resources. Non-sustainable practices, such as trawling, resulting from a poor fisheries management, lead to an imbalance of these trophic webs.

Phytoplankton growth depends on the inorganic nutrients that reach the illuminated area of the water column. Therefore, it becomes essential to understand the physical processes that regulate the presence of these nutrients and to characterize their continental sources. In addition, phytoplankton populations are regulated by their direct consumers, such as filter feeders, which keep them in a certain balance. However, in coastal areas, with a high anthropogenic input of nutrients, this balance can collapse, giving rise to phytoplankton blooms that cause a loss of biodiversity and a decline in water quality, also affecting the tourism sector. However, this proliferative capacity of phytoplankton is not always negative. Indeed, in the open sea, the phytoplankton that is not consumed or recycled settle down at the bottom, immobilizing the atmospheric CO_2 captured during the photosynthesis, thus mitigating the greenhouse effect responsible for global warming.

In the last decades, failures in the fisheries management of several commercial species have led to their overexploitation, causing sharp decreases in the populations that resulted in non-sustainable situations. To tackle this problem, we need to widen our current knowledge of the biology of marine species. This can be done, for instance, by using new tools such as omic techniques, or by the implementation of non-invasive monitoring technologies to reach inhabiting areas of difficult access. In addition, a good co-management of fishing involving the scientific community, the fishermen, the administration and other organizations is essential not only to monitor and supervise marine resources but also to preserve biodiversity. But the use of marine living resources is not only aimed at their consumption. Many marine species constitute an important source of natural products with applications in different fields, such as the use of algae in the pharmaceutical or energy industries, or the use of animals as experimental models in biomedicine. The need to ensure the well-being of these animal models is an ethical and moral obligation that researchers have with our planet and society.

According to the United Nations, “the oceans are the vulnerable heart of our planet”, so a deep knowledge and a responsible management of the oceans are the key to the development of a sustainable blue economy.

Acknowledgements: We sincerely thank Glynn Gorick for his gentleness sharing his beautiful recreation of the oceanic food webs.

3.1. The heat collector-distributor ocean-atmosphere system

Dorleta Orúe-Echevarría, Ignasi Vallès-Casanova, Josep L. Pelegrí

The climate of the Earth depends mainly on the distance to the Sun and the temperature of this star. This sets the insolation (energy per unit area) arriving to the earth's surface. However, the actual mean temperature of the Earth and its geographic distribution is related to the ocean-atmosphere system, depending on two types of processes: those controlling the local radiative equilibrium and those responsible for the heat distribution between different regions.

On one hand, the global radiative equilibrium is determined by the greenhouse gases and the planetary albedo. On the other hand, the heat distribution depends on the intensity and direction of both ocean currents and atmospheric winds, as well as on the heat exchange between the atmosphere and the ocean. Local temperatures, however, are also largely influenced by the high heat-storing capacity of the oceans. In this essay, we will focus on the way these key elements set the annual-mean temperature over the Earth, but we will also inspect how the temperature is continuously oscillating in space and time, far from steady state.

Albedo and greenhouse gases

The sun is so warm (about 5600°C) that it irradiates at relatively short wavelengths (peaking at 0.5 μm), which can cross the atmosphere and reach the earth's surface. However, the earth receives only a very small fraction of the incoming solar radiation (the earth-sun vision factor, or fraction of the sky spanned by the Earth, is very small [about 2.2×10^{-5}]), so the earth's temperature is much lower, and its radiation has much longer wavelengths (about 10 μm).

As a consequence, the Earth's emission can be blocked by radiative-active greenhouse gases, heating the atmosphere. The atmosphere then splits its long-wave backward radiation in two halves, one out to space and another back to the Earth, further warming its surface (Figure 1). The outcome is that the earth heats up to a temperature at which the incoming short-wave radiation and half of the atmosphere's radiation are equal.

However, this is only part of the story, as not all the solar radiation is absorbed by the Earth surface. Part of it is reflected back to space by either the atmosphere or by the earth's surface (Figure 1). This is named planetary albedo, which has a global value of about 30% but varies from about 25% in the tropics, characterized by dark jungle and open deep waters, to 65% at high latitudes with abundant reflecting ice and snow.

In the absence of greenhouse gases and assuming zero albedo, the mean temperature of the entire Earth would be about 5.6°C, much lower than its current mean temperature of about 15.0°C. This temperature rise is mostly caused by the greenhouse gases, which largely overcome the cooling effect of albedo.

Further changes in the radiative balances will determine the evolution of climate over the coming decades. By the end of the 21st century, predictions indicate that the increase in greenhouse gases will induce further blockage of long-wave radiation by the atmosphere. This increase and, to a lesser degree, the decrease in polar albedo, will rise the Earth's mean temperature. Depending on the greenhouse emission scenario, this mean temperature will likely

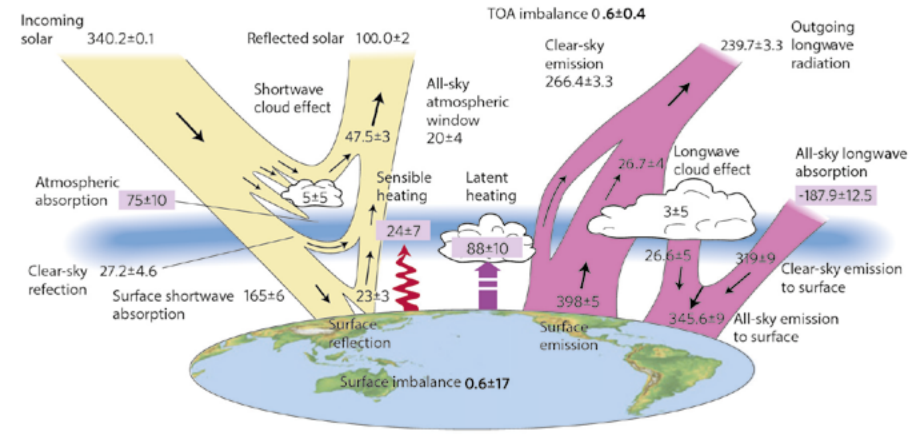

Figure 1. Main processes controlling the global annual-mean energy balance in the Earth for the period 2000–2010 (reproduced from Stephens *et al.* 2012). TOA stands for top of the atmosphere and the values represent energy fluxes per unit area, expressed in watts/m^2. The Earth's surface experiences an imbalance of 0.6±0.17 watts/m^2 that is driving the warming of our planet; heating is largely regulated by the oceans, which absorb about 90% of this excess energy input.

reach between 16.8°C and 18.3°C (Roca and Pelegrí 2020).

Ocean currents and atmospheric winds

Tropical regions, where the solar radiation arrives nearly perpendicular to the Earth's surface, have the largest annual-mean amount of heat arriving per unit area, which has to be distributed to other regions of the Earth. In the absence of oceans and atmosphere, this heat could only be transferred through conduction along the lithosphere. This would be extremely inefficient, with a latitudinal transport of the order of only 10^4 watts. If we consider the presence of oceans and atmospheres but without currents and winds, the latitudinal heat transfer would only increase to about 10^6 to 10^7 watts. In order to have the observed latitudinal transport, of the order of 6 PW (6×10^{15} watts), we require the presence of winds and currents.

Oceans and winds share roughly equally the latitudinal heat transport at low latitudes, but winds dominate at intermediate and high latitudes. However, because of the high heat capacity of water, the oceans can store about 1000 times more heat than the atmosphere. Hence, the oceans are indeed the main regulator of the global temperature change. Indeed, the oceans have incorporated about 90% of the Earth's heat anomaly associated with anthropogenic effects, but their average temperature has increased by only about 0.15°C, which is ten times less than the 1.5°C mean temperature increase at the sea surface.

Temporal variability

The Earth, however, is far from steady. On the contrary, it is a pulsating entity, which experiences all sorts of spatiotemporal oscillations from global to local scales. Some of these pulsations are guided by astronomical motions, as happens with the diurnal and seasonal cycles. But other variations are far more irregular, as they respond to the internal non-linear dynamics of a very complex system. In some cases, such as the glacial-interglacial cycle, astronomic forcing combines with internal feedback to produce asymmetric temporal cycles.

Once again, the ocean plays a very important mitigating role at different temporal scales, as it incorporates heat during the daytime or during the summer season and releases it back to the atmosphere at night or during winter. However, the system is highly non-linear, with multiple feedback mechanisms. Atmosphere-ocean heat exchange relies on the structure of the water column, which is tied to the wind regime, which in turn depends on the heat distribution in the

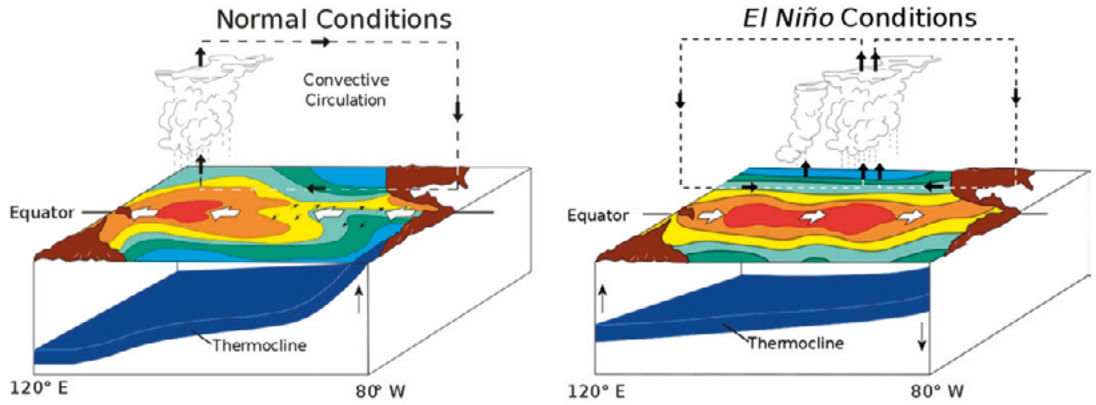

Figure 2. Sea surface temperature (reddish/bluish colours represent relatively warm/cool waters) and currents (white arrows) during normal and *El Niño* sea conditions; the shape of the thermocline, which separates the surface warm waters from the intermediate and deep cold layers, is also shown. The atmospheric counterpart (known as the Southern Oscillation) affects the near-surface and altitude winds (black arrows), as well as the precipitation patterns (adapted from NOAA 2021).

surface layers, and back to the heat exchange at the air-sea interface. Figure 2 illustrates the main elements for the *El Niño*-Southern Oscillation phenomenon, which is one of the most noteworthy examples of this air-atmosphere feedback mechanism (Rasmusson and Carpenter 1982).

The non-linear complexity of the Earth system makes it very difficult to produce accurate weather or climate predictions. Actually, the smaller in size and shorter in time the perturbations, the lesser is our skill to make reliable mid- and long-term forecasts. This is why, for example, we can only predict weather patterns for periods shorter than 10 days. This time window increases to several months when dealing with phenomena of inter-annual variability, such as *El Niño* or the North Atlantic Oscillation. Despite their irregular nature, these oscillations evolve over periods long enough to allow identifying when and how an event develops (Vallès-Casanova *et al.* 2020).

The anthropogenic perturbation is neither astronomical nor internal. It affects both the albedo and the greenhouse gases, causing significant changes in the global heat budget, and it also disturbs the regional and global atmospheric and oceanic circulation patterns. The ocean, thanks to its extraordinary heat absorbing capacity, is surely restraining and slowing down these changes, giving humankind an opportunity to decide what planet we wish to leave for the coming generations.

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3.2. Physical basis of ocean primary production

Josep L. Pelegrí, Dorleta Orúe-Echevarría, Anna Olivé Abelló, Ignasi Vallès-Casanova

Primary production refers to the synthesis of organic matter from water and atmospheric or aqueous carbon, which occurs primarily through the conversion of solar energy into chemical energy. The rate of energy transformation is named primary productivity, expressed with units of carbon per area and time (gross primary productivity refers to the total amount of energy, but some of it is used for the organisms' self-maintenance, including respiration, leading to net primary production as the commonly used variable). Primary production depends on the availability of light, (inorganic) nutrients and water. In the oceans, there is plenty of water but light and nutrients are often limited for various reasons, in particular because they also depend on the level of primary production itself.

Short-wave solar radiation is not able to penetrate easily into the ocean, so primary production is restricted to the surface layers, which is named the euphotic zone. Further, the penetration of solar radiation depends on the concentration of phytoplankton in water. For a moderate chlorophyll concentration of 1 mg m^{-3}, only about 1% of the total solar radiation reaches a depth of 40 m (0.1% at 60 m) (Talley *et al.* 2011). Additionally, daylight time changes with latitude and season. In tropical regions, the length of daylight does not change substantially from one season to another, but at high latitudes light is much reduced and even disappears fully in winter, so primary production may cease.

A sustained level of primary production in the sunlit surface layers requires a constant supply of nutrients from the subsurface waters. At high latitudes and during wintertime, primary production is limited because of the low insolation, leading to an increase in the nutrient levels in surface waters. This sets the right conditions for the development of the spring bloom, when suitable insolation levels are reached. In tropical and subtropical waters, and at high latitudes after spring, sustained primary production requires a continuous supply of nutrients, either through vertical mixing or through nutrient-loaded subsurface currents that approach the sea surface (Pelegrí *et al.* 2019).

Spatiotemporal distribution of primary production

Wind-induced vertical mixing is the main factor regulating the mean vertical distribution of primary production. Mixing stirs the upper layers of the water column, leading to the creation of a surface mixed layer in the uppermost portion of the water column, typically several tens of metres thick, where many water properties are homogenized (temperature and nutrients among others). Vertical mixing also has two other effects: it supplies subsurface nutrients to the euphotic layers and it is an effective stirrer that raises subsurface water parcels to the sunlit region. Temperature is highest and nutrients are lowest in the surface mixed layer, with a sharp decrease in temperature and an increase in nutrients at the base of the mixed layer, respectively known as the (seasonal) thermocline and nutricline. Primary productivity is enhanced in the nutricline, simply because this vertical location provides the optimal combination of light and

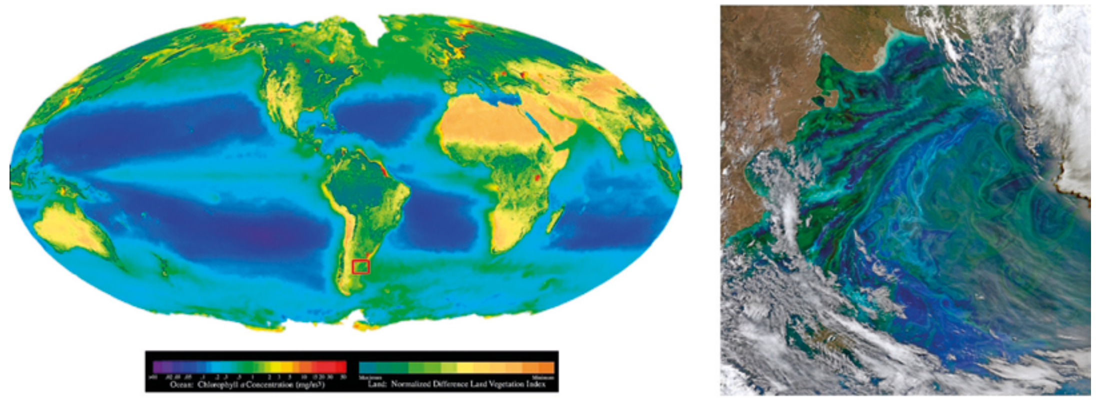

Figure 1. A, classical image of the SeaWIFS-derived (January 1998 to December 2019) average sea-surface chlorophyll distribution (NASA 2012), with the red square showing the location of the Brazil-Malvinas Confluence (BMC). B, false-colour snapshot of a bloom in the BMC on 2 December 2014 (NASA 2014).

nutrients for photosynthesis, setting the locus of this deep (or subsurface) chlorophyll maximum.

In addition to the seasonality in insolation at high latitudes, primary production changes in space and time according to how swift nutrients reach the surface mixed layer (Figure 1). Generally, we may say that the faster nutrients are supplied to the surface layer, the greater primary productivity will be (although there are some exceptions, such as in iron-limited subantarctic regions). In subtropical and temperate regions, this happens during autumn, as the winds incorporate nutrient-rich waters to a progressively thickening surface mixed layer.

In other regions, efficient nutrient supply to the euphotic layer occurs during the entire year, as the winds cause the divergence of the surface waters, which are then replenished through the upwelling (upward advection) of nutrient-rich subsurface waters. This happens extensively in the eastern boundary of the subtropical gyres (e.g. the Canary upwelling region), in equatorial regions and in the Southern Ocean. It also happens in western boundary currents, such as the Gulf Stream, and their poleward extension into the subpolar gyres. In the North Atlantic, this gives rise to one of the most spectacular phenomena in nature: the spring bloom of the North Atlantic Ocean. Remarkably, deep waters are formed in these highly-productive subpolar regions: the sinking waters carry large loads of organic matter to the deep abyssal ocean, where it will remineralize to establish the high deep-water nutrient concentrations.

Primary production not only changes at seasonal scales but also experiences inter-annual and long-term fluctuations. One noteworthy example is the glacial-interglacial periods. During the last three million years, the Earth has changed between less and more energetic periods, with a substantial effect on global primary production. Through interglacial periods, deep-water formation and the global overturning circulation are intensified, leading to increased deep remineralization and increased nutrient supply to the surface ocean, which enhance global primary production. During glacial periods the global circulation weakens and fewer nutrients are available, so global production decreases (Pelegrí *et al.* 2013).

Anthropogenic effects and the future ocean

The main direct anthropogenic effect on primary production is increased eutrophication, whereby nutrients are added to the coastal ocean as a result of industrial or farming wastewaters, potentially leading to the degradation and deoxygenation of coastal ecosystems and the production of harmful algal blooms (Berdalet *et al.* 2022).

Climate change is also having a very important effect on primary production, in many dif-

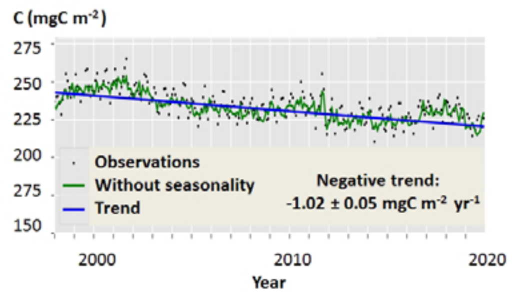

Figure 2. Monthly mean values of global net primary productivity, showing a negative linear-fit trend (Copernicus 2021).

ferent manners. One way is through increased warming of surface layers, which leads to increased vertical stratification, inhibiting vertical mixing and nutrient supply to the surface layers. Further, mean winds in the open ocean appear to be diminishing because of weaker thermal latitudinal gradients, contributing to decreased downwelling of surface waters at mid-latitudes and decreased upwelling of subsurface waters in equatorial and high-latitude regions. Other factors are the decrease in freshwater discharge, particularly in subtropical regions, and the weakening of the global meridional overturning circulation, which reduces the supply of nutrients to high latitudes.

In contrast, coastal winds appear to be rising as a result of the increased thermal gradient between land and ocean masses, leading to more intense upwelling in the eastern boundary subtropical regions. Other factors enhancing primary production are the seasonal loss of sea ice at high latitudes, the increase in atmospheric dust transport and the continuously rising carbon dioxide concentrations in the atmosphere.

Global trends in primary production are indicative of a sustained reduction during the last two decades (Figure 2), although regional trends show substantial differences. The evolution of primary production in the future ocean is hard to predict, not only because of the competition between those factors that control the supply of nutrients to the surface ocean but also because of the difficulty in forecasting the changes in stratification and circulation patterns. Equitable policies and sustainable development are the only pathways that can guarantee a healthy and productive future ocean.

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3.3. Controls of phytoplankton dynamics in the Catalan Sea

Marta Estrada, Miquel Alcaraz, Laura Arin

The Mediterranean Sea can generally be considered as oligotrophic although it has a suite of fertilization mechanisms at various spatial and temporal scales that are responsible for hotspots of phytoplankton biomass and production. In this essay, we review some of these mechanisms in the Catalan Sea.

Drivers of fertility in the Catalan Sea

The marine currents in the NW Mediterranean flow from the NE to the SW along the Catalan coast and return towards the NE near the Balearic Islands. This cyclonic gyre leaves a divergence zone in the middle, separated from the coastal waters by shelf-slope fronts.

In winter, cooling of the surface layers facilitates mixing of the water column and the input of nutrients from deeper waters into the euphotic zone. In the Liguro-Provençal Basin, at the northern boundary of the Catalan Sea, the doming of the isopycnals, in combination with heat loss and evaporation caused by strong and dry northerly winds, may lead to deep convection and vertical mixing down to the bottom, with introduction of nutrients into the upper layers and formation of deep water that spreads around the basin. Deep convection is an important driver of the phytoplankton dynamics and production not only locally but also in distant zones of the basin. For example, on 25 March 2005, surface chlorophyll *a* reached 7 mg m^{-3}, among the highest values measured in the region, and on 22 March 2009, with 2.3 mg m^{-3} of surface chlorophyll *a* (Figure 1B), vertically integrated (0–80 m) primary production attained 1800 mg C m^{-2} d^{-1} (Estrada *et al.* 2014).

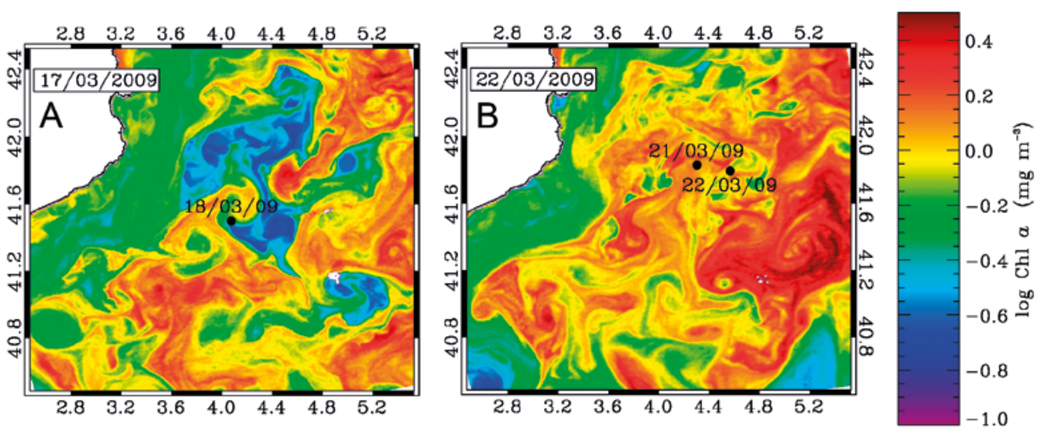

Figure 1. Remote sensing-derived images of chlorophyll *a* distribution in the NW Mediterranean on 17 (A) and 22 March 2009 (B). Note the increase in chlorophyll *a* concentration from 17 to 22 March. The low chlorophyll *a* (blue) area on 17 March is a result of deep convection. The black dots indicate station positions during the Famoso 1 cruise. Reprinted from Estrada *et al.* (2014), with permission.

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Between late winter and early spring, the increase in irradiance and the start of thermal stratification induce the growth of an intense phytoplankton bloom in the surface waters. Later on, stratification intensifies and a steep vertical density gradient (the pycnocline) develops between the upper mixed layer and the deeper waters. The growth of phytoplankton depletes the nutrients (such as nitrate, phosphate and silicate) in the upper, illuminated part of the water column. Under these conditions, the balance between nutrients diffusing from below the pycnocline and light availability from above leads to the appearance of a deep phytoplankton and chlorophyll maximum, accompanied by accumulations of zooplankton (Estrada *et al.* 1993, Alcaraz *et al.* 2007). In the divergence region, the pycnocline is shallower and the higher light availability enhances phytoplankton growth in the deep maximum. In turn, the shelf-slope fronts bordering the gyre feature eddies, meanders and filaments, which together with the ageostrophic circulation (Estrada *et al.* 1999) can generate fertilization events. Often, a phytoplankton peak occurs in autumn, when cooling of the surface water breaks the pycnocline.

Other important contributions to nutrient enrichment in the Catalan Sea originate from continental water inputs and from atmospheric deposition. In the NW Mediterranean, the most influential rivers are the Rhône and the Ebre; however, discharges from smaller rivers and wastewater overflows may also be locally prominent, in particular after storms.

The phytoplankton succession

The fluctuations of phytoplankton biomass during the seasonal cycle are associated with marked changes in the composition of the community. The succession of dominant groups from the winter-spring peak to summer stratification was characterized by Ramón Margalef as a function of water turbulence intensity and nutrient availability (see Alcaraz and Estrada 2022). Fast-growing groups such as diatoms dominate when turbulence and nutrient concentration are high, while in stratified and nutrient-poor waters dinoflagellates, which are motile and can migrate up and down in the water column, are more abundant. Coccolithophores tend to thrive in intermediate situations. In the last few decades, new methodologies for phytoplankton categorization based on pigment markers or on molecular genetic techniques have provided information on the distribution of taxa such as cyanobacteria and many flagellates, which, owing to their small size or lack of distinctive morphological features, had not been suitably quantified in earlier studies.

What can we learn from long-term series?

As happens on land, there are strong interannual fluctuations in the patterns of phytoplankton succession over a seasonal cycle. In addition, global anthropogenic change may interact with natural variability in ways that we do not yet know. Therefore, ascertaining drivers of change and identifying long-term trends requires the collection of long time series of environmental and biological ecosystem variables at appropriate resolution.

As a contribution to these goals, the Institut de Ciències del Mar (ICM-CSIC) maintains several temporal series in Catalan Sea waters. In the littoral of Barcelona, the Coastal Ocean Observatory (https://coo.icm.csic.es/ca) measures several parameters in real time and, since March 2002, has carried out monthly surveys assessing environmental and biological variables. This long-term series has given important insights into the functioning of the coastal planktonic ecosystem of the Catalan Sea. For example, Arin *et al.* (2013) found that river runoff was the main source of nutrients for the winter-spring maxima of 2003 and 2004, while fertilization episodes fuelling the phytoplankton blooms of 2005 and 2006 were due to the intrusion of offshore waters associated with the strong mixing events of the unusually cold and dry winters of these two years (Figure 2). In the Bay of Blanes Observatory series (http://bbmo.

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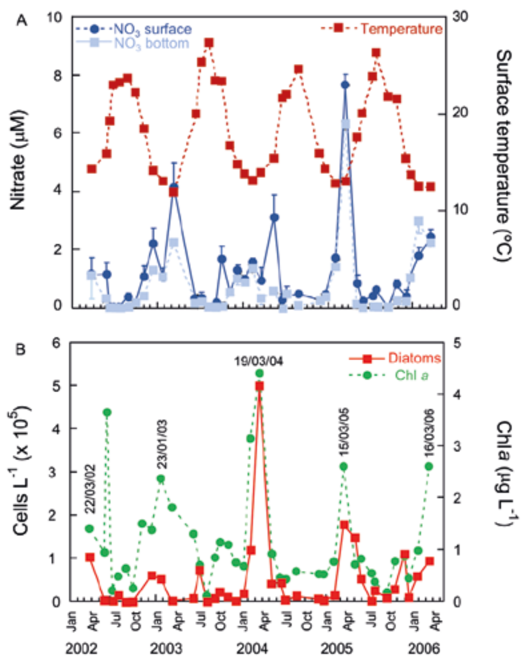

Figure 2. A, surface and bottom nitrate concentration (median + median absolute deviation) from eight sampling stations of the Coastal Ocean Observatory off Barcelona (March 2002 to March 2006) and surface temperature showing the annual cycle; B, surface chlorophyll *a* (Chl *a*) and diatom abundances from the same period at a representative station.

icm.csic.es/), the study of 14 years (2000–2014) of samples was used to characterize the seasonal cycle of the main phytoplankton groups and showed that, superimposed on the general pattern, diatoms and prasinophytes (a group of flagellates) proliferated in response to fertilization from storm runoff (Nunes *et al.* 2018). This series also revealed a decreasing trend in chlorophyll *a* concentration that could be attributed to a reduction of nutrient availability due to improvements in the wastewater treatment in the zone.

Concluding remarks

The Mediterranean has been considered as a reduced and more accessible model of the world's oceans. In a similar way, the Catalan Sea concentrates many of the ecological and socio-economic processes occurring in the whole Mediterranean. Information from oceanographic surveys and time series in the Catalan Sea and other marine areas around the world helps to reveal how interactions between natural and anthropogenic variability influence the pelagic ecosystem and highlights the importance of long-term monitoring for improving future projections and management decisions.

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3.4. The power of unicellular primary producers

Pedro Cermeño, Carmen García-Comas, Caterina R. Giner, Ramiro Logares, Cèlia Marrasé, Ramon Massana, Carlos Pedrós-Alió, Maria Montserrat Sala, Rafel Simó, Javier Tamames, Sergio Vallina

Marine phytoplankton, including cyanobacteria and microalgae, dominates primary production across two thirds of the earth's surface, sustaining virtually all marine life and exerting a fundamental control over global climate through carbon sequestration into the deep ocean. These unicellular photoautotrophs are responsible for roughly 50% of global net primary production, which is equivalent to producing 50 gigatons of organic carbon (C) per year (about 140 million t per day). Phytoplankton produce a massive amount of organic C despite representing only 1% to 2% of the photosynthetic biomass on earth, thus reflecting their extraordinarily high turnover rate. Almost all of the phytoplankton standing right now in the world's oceans will be consumed and produced again in a week or less. Unlike terrestrial ecosystems, where plant biomass dominates the landscape (imagine a lush rainforest), the living seascape is dominated by heterotrophic microorganisms, including bacteria, protozoans, ciliates and tiny crustaceans, whose global biomass exceeds the biomass of marine primary producers by up to five times (Bar-On *et al.* 2018). This inverted biomass distribution pattern is one of the most prominent hallmarks of ocean plankton ecosystems, which rely on the activity of heterotrophic microorganisms to continually recycle photosynthetic biomass and replenish fast-growing phytoplankton with essential nutrients. This close coupling between microbial primary producers and recyclers forms the so-called microbial food web (Azam and Malfatti 2007), which keeps ocean plankton ecosystems close to steady state. However, in some cases, ocean currents, continental runoff and dust storms, among other events, bring new nutrients to the surface, boosting primary productivity and moving plankton ecosystems away from the steady state. Because marine primary production incorporates roughly 6.6 moles of carbon dioxide (CO_2) for every mole of nitrogen, the input of new nutrients into the sunlit layer of the ocean reduces the concentration of dissolved CO_2 in surface waters. The resulting "new" primary production (to differentiate it from the "recycled" primary production) takes heterotrophs by surprise and they cannot instantly consume the excess primary production. As a result, a large fraction of this "new" primary production ends up being exported to the depths of the ocean. This phenomenon, called the biological C pump, generates a CO_2 deficit on the ocean surface, which is offset by the absorption of CO_2 from the atmosphere. In this way, the ocean's biological pump helps mitigate the greenhouse effect and cool the earth's climate.

Understanding the ecological and biogeochemical functioning of plankton ecosystems is key to harnessing the power of unicellular primary producers in order to develop solutions that help address some of the current challenges facing our society, such as global warming and food shortages. Because many of these solutions require the natural processes to be accelerated, before explaining how these microscopic primary producers could contribute to this global effort, let us start by illustrating here how they impacted the earth system in the geological past. The ultimate goal is to condense into decades/centuries the changes that nature took hundreds of thousands of years to achieve.

The powerful plankton

Two mechanisms are thought to have increased the ocean's biological potential to boost primary production, fuelling marine food webs and reducing the concentration of CO_2 in the atmosphere. The first one involves an increase in the oceanic inventory of inorganic nutrients. Because primary production in many oceanic regions is limited by the availability of essential nutrients, such as nitrogen, phosphorus and iron, an increase in nutrient input into the ocean will have boosted global ocean primary production, as well as the fraction of primary production transferred to upper trophic levels and exported to the depths. The second mechanism has to do with changes in the stoichiometry of the phytoplankton biomass and detrital fractions in comparison with that described by Alfred C. Redfield, who found that the ratio between carbon (C), nitrogen (N) and phosphorus (P) is a nearly constant 106:16:1 throughout the world's oceans in both phytoplankton biomass and in dissolved nutrient pools. An increase in these elemental ratios would involve an increase in the amount of C exported per unit of N or P entering the surface ocean. There is evidence that these two mechanisms have acted in the geological past (Falkowski 2012), by i) increasing marine export production, ii) promoting the formation of vast deposits of oil and gas, and iii) helping cool the earth's climate.

The prospect of algaculture

Our deep understanding of marine ecosystems gives us, as marine scientists, the ability to invent smart solutions to address some of today's most pressing social and environmental challenges. For centuries, conventional agriculture has struggled to prevent the collapse of food crops, which are often ruined by pests and diseases. Decades of agricultural research have enabled the development of crop protection measures that have resulted in previously unthinkable crop yields. For example, corn yield (i.e. corn production per unit of land used) has increased five-fold over the last 80 years, thanks to some extent to breakthroughs in pest management (Figure 1). Unicellular primary producers are three to four times more efficient than terrestrial plants at converting sunlight energy into biomass and can achieve biomass production yields that are up to one order of magnitude higher (Figure 1). However, their use as a sustainable source of feedstock for human food, animal feed or biofuels remains untapped. Algaculture or phycoculture, hereinafter the cultivation of cyanobacteria and microalgae using wastewater or seawater, has incredible potential to become an important source of biomass for the future, as well as an efficient sink of CO_2 from industrial flue gases (Araújo *et al.* 2021). However, the large-scale implementation of algaculture suffers from the same problems that conventional agriculture has faced for centuries. As discussed in the opening paragraph, hetero-

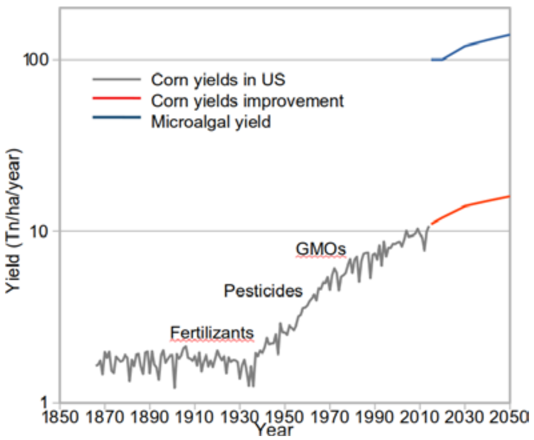

Figure 1. Average maize yields in the United States from 1866–2014, based on data from the United States Department of Agriculture (USDA) and the UN Food and Agriculture Organization. The yields remained relatively flat until the 1930s. In the period since 1940, yields have increased more than five-fold thanks to irrigation, fertilizers, improved pest management and genetically-modified organisms. Microalgae biomass production yields are one order of magnitude higher than current maize yields and are expected to increase substantially as the currently underdeveloped algaculture technology improves strain productivity and pest resistance.

trophic microorganisms can take over plankton communities in a matter of days, leading to the failure/collapse of biomass production systems. Furthermore, cyanobacteria and microalgae have enormous nutritional (fertilizer) needs, which hinder the global expansion of algaculture for mass production of low-price commodities such as food, feeds and biofuels. Protecting microalgal crops from biological consumption, pests and diseases and finding ways to re-supply nutrients and CO_2 in order to enhance, respectively, biomass production and the biological capture of C are critical to make algaculture truly sustainable and profitable in the coming decades.

The advent of new technologies, such as genomics, has enabled marine scientists to gain a deeper understanding of how unicellular primary producers thrive, die and decay in natural plankton ecosystems (Pedrós-Alió 2006). This knowledge provides us with extremely valuable information for exploring ways to accelerate natural processes and help i) provide a sustainable source of biomass for food and biofuels and ii) reduce atmospheric CO_2 emitted from burning fossil fuels by capturing it in the form of refractory organic compounds, just as nature has been doing since the origin of oxygenic photosynthesis about 2.5 billion years ago. Just as agriculture represented a momentous change in the history of humanity and of our planet, the expansion of algaculture is called to play a crucial role in the evolution of our society towards a more habitable future planet.

Acknowledgements: The ideas embodied in this essay are part of the objectives of the PRODIGIO project "Developing early warning systems for improved microalgae PROduction and anaerobic DIGgestIOn". The PRODIGIO project has received funding from the European Union's Horizon 2020 Research and Innovation programme under grant agreement no. 101007006.

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3.5. Omics tools for managing living resources and protecting ocean biodiversity

Francesc Piferrer

Omics tools encompass a set of technologies aimed at the collective analysis and characterization of groups of molecules present in living organisms, such as DNA, RNA, proteins and their modifications (Figure 1).

The proper management of ocean ecosystems and the sustainable use of marine resources can benefit from the implementation of omics tools. It is therefore not surprising that entities such as the National Oceanic and Atmospheric Administration, a US government agency, have placed great hopes in them. It is envisioned that their application will serve to improve systems for monitoring, surveillance and management of living resources and biodiversity conservation in a changing ocean, all aimed at supporting the blue economy (Godwin *et al.* 2020).

Below I present a brief overview of how omics tools are increasingly being used in the management of living resources and the identification and protection of ocean biodiversity, and how they can be used to identify the consequences of climate change on marine life.

Applications to fisheries and aquaculture

Genomics has great potential for identifying new species and varieties, which is very important for both fisheries and aquaculture, where there is a lot of genetic variability that is still not well characterized (Mohanty *et al.* 2019). The development of arrays of single nucleotide polymorphisms (SNPs) for most species of interest in aquaculture is already a reality, making it possible to go one step beyond classical genetic selection with what is known as genomic selection, i.e., selection based on information provided after examination of a set of informative SNPs distributed throughout the genome (Houston *et al.* 2020). Similar applications in fisheries will provide a very precise understanding of the genetic structure of populations, which, together with other techniques under development such as environmental DNA analysis, will allow a better understanding of the resources of an ecosystem.

Epigenetics integrates genomic and environmental information and can explain much of the phenotypic variance that is not explained by genetic variance. Advances in epigenomics applied to aquaculture have made it possible to identify the basis of resistance to diseases that cannot be explained genetically and the development of sex-predictive tools. It is expected that epigenetic markers will soon be available that can predict stock performance under certain environmental conditions. In fisheries, examination of DNA methylation changes at specific loci in the genome has led to the development of the first epigenetic clock in fish (Anastasiadi and Piferrer 2020). The application of these clocks in species of high commercial interest, such as cod and hake, will make it possible to determine the age of fish without the need for otolith analysis, which has been used so far.

Nutrigenomics is a variant of transcriptomics that aims to find out how food composition affects gene expression and how this in turn influences the metabolism, growth and health of animals. Proteomics and metabolomics are of great interest in studies aimed at finding out the composition of muscle, the most important and edible part of fish. Other advances resulting from the application of omics tools include the identification of pathogens, disease resistance and stress tolerance.

Applications in conservation biology

Omics tools are ideal for obtaining a good picture of the physiological state of organisms as a function of environmental changes. The identification of aquatic pollution caused by natural products or contaminants (such as toxins produced by certain types of algae), or by anthropogenic pollutants, is one of the areas in which most efforts are being made. Biomonitoring, or monitoring using living organisms as sentinels, is a common way of determining the state of contamination of aquatic ecosystems. The incorporation of omics tools into environmental monitoring programmes has only just begun but has a great future because of its ability to include different types of information towards a common goal (Van Aggelen *et al.* 2010).

Finally, the integrative power of omics tools in giving a holistic view of the state of communities is a powerful argument for their use in monitoring the effects of climate change on marine ecosystems.

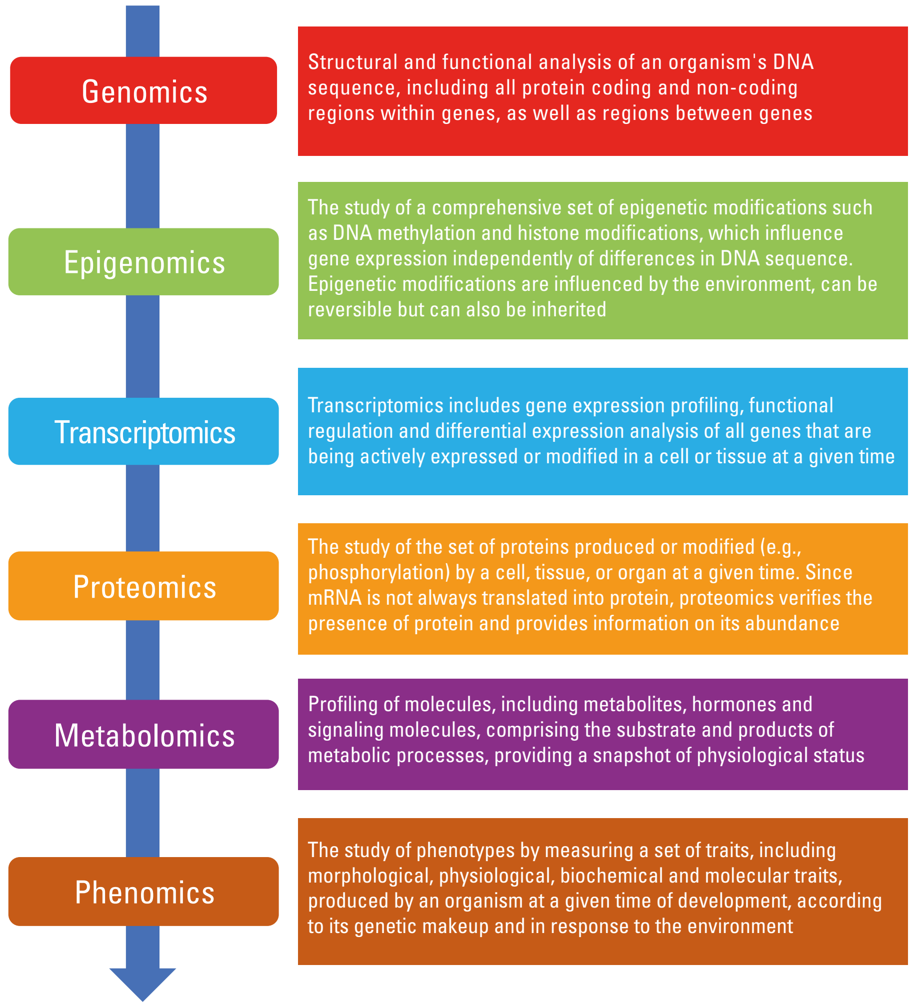

Figure 1. The omics techniques, their relationship to each other and a brief description of each one.

Conclusions and perspectives

The progressive reduction in the cost of sequencing will increase the number of genomes available to us, which will result in a better understanding of marine resources and biodiversity. A major challenge is to develop new tools for processing the massive amounts of data generated from genome sequencing projects and their integration with phenotypic data. Combining these tools with genome-wide association studies will allow the most informative phenotypic changes to be identified with the underlying genomic ones (Figure 1).

Advances in the development of omics techniques will improve the quality and cost of biological data obtained in comparison with traditional observational techniques. Once omics tools have been applied to solve a problem such as how a species or community responds to global warming, it will be possible to develop markers compatible with the analysis of a large number of samples in a very short time and at a very affordable price. These markers will undoubtedly be very useful in environmental monitoring programmes.

The application of omics tools to the study of living resources and biodiversity in the oceans requires the collection of a considerable number of samples that can be representative of the species, community, phenomenon or geographical area of interest. Therefore, one of the most important challenges is the management of technical and biological variation. In this stimulating and necessary task, it is necessary to add the need for the training of personnel specialized in the use of these tools, with a multidisciplinary vision of the problems. In conclusion, there is a great future in the application of omics tools to marine sciences, and the necessary resources should be allocated for their implementation.

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3.6. Animal welfare in marine science

Mercedes Blázquez, Guiomar Rotllant, Roger Villanueva

Animal welfare is considered as the well-being of non-human animals and covers the way they cope with the conditions in which they live. An animal is in a good state when it is healthy, well nourished, safe, capable of expressing its innate behaviour and not suffering any pain, fear or discomfort. However, demonstrating whether an animal experiences pain is not an easy task. Several endpoints need to be assessed depending on the animal group and the developmental stage. In this essay, we will focus on marine *fishes* in representation of vertebrates, *cephalopods* as invertebrate models, which are both subject to strict rules and regulations in terms of welfare in EU countries, and *crustaceans*, because they will soon be subject to these regulations. We chose these animal groups because they are research models of commercially exploited species at the ICM-CSIC.

Ethical considerations in animal research: legislation

Fish are the most diverse group of vertebrates, and their use as models in biomedicine, ecology and animal production has increased considerably during the past few years. Moreover, their evolutionary position at the start of vertebrate radiation, their ability to adapt to different environmental conditions, and their similarities at the molecular level with other vertebrates, including humans, make them excellent models in very diverse disciplines. In many countries, the use of fish as experimental animals is tightly regulated and includes recommendations for farmed fish. European states are ruled by Directive 2010/63/EU, amended by Regulation 2019/1010/EU. In addition, some of them also have specific laws that can be even more restrictive, such as the Spanish RD 53/2013. Cephalopods have been subject to the same fish welfare regulations since 2013 in EU countries. These molluscs are considered among the most advanced invertebrates, with relatively large multi-lobular brains and developed nervous systems supporting rich behavioural repertoires and a sophisticated sensory world. Cephalopods exhibit cognitive and spontaneous behaviours indicative of affective pain experience, and the use of suitable care and welfare should be applied, in addition to analgesics, anaesthetics and a humane endpoint when necessary (Fiorito *et al.* 2015, Crook 2021).

The assessment of pain is crucial for improving animal welfare. Sneddon *et al.* (2014) defined two key concepts to evaluate the potential for pain in invertebrate and vertebrate taxa: 1) responses to noxious stimuli that could affect animal neurobiology, physiology and behaviour; and 2) a change in their motivational state. The study considers 17 criteria as animal-based indicators for pain. Crustaceans are not yet included for protection under EU legislation at the moment of killing based on the fact that they do not exhibit suffering or pain. However, the European Food Safety Authority has stated that "The largest of decapod crustaceans are complex in behaviour and appear to have some degree of awareness. They have a pain system and considerable learning ability and all decapods should receive protection" (EFSA 2005). Stunning methods for decapod crustaceans are obligatory in Switzerland, New Zealand and some Australian states and recommended in Norway. Considering recent experimentation, they fulfil all 14 criteria for which they have been tested (reviewed in Passantino *et al.* 2021). Hence, there is no compelling argument to dismiss the idea of pain in this taxon.

Figure 1. Animal Research at the ICM-CSIC. General view of one room at the Aquaria and Experimental Chambers facility (ZAE) where authorized animal research takes place (A). The species stocked and bred include the following: fish: sea bream, *Sparus aurata* (B) and European sea bass, *Dicentrarchus labrax* (C), key species for Mediterranean aquaculture; zebrafish, *Danio rerio* (D), used as a vertebrate model species for a large number of research disciplines. Cephalopods: cuttlefish *Sepia officinalis* (E); octopus, *Octopus vulgaris* (F); eggs from cuttlefish (G). Crustaceans: Norway lobster, *Nephrops norvegicus* (H); hermit crab, *Dardanus arrosor* (I); and Mediterranean shame-faced crab, *Calappa granulata* (J).

Humane techniques in animal research: The 3Rs principle

All the welfare regulations and directives are based on the 3Rs principle: reducing, refining and ultimately replacing the use of animals for scientific purposes. This principle lays the foundations for the achievement of humane techniques in research. *Reduction* covers any procedure that results in a smaller number of animals being used in a given procedure in order to obtain reproducible and trustable results. *Refinement* consists in modifying any condition of housing, husbandry or care during the lifespan of an animal in order to minimize pain, distress, suffering and physiological changes and enhance its well-being. *Replacement* includes applying methods that do not involve the use of living animals. It can be achieved by other alternative techniques, including *in vitro* systems (tissues and cells), *in chemico* systems (synthetic macromolecules as proxies), *in silico* systems (computer-based models), and the promising 3D bioprinting.

The ICM's commitment to animal welfare

Welfare is closely related to the housing and maintenance conditions of the animals. In this regard, the ICM-CSIC has joined the Concordat on Openness on Animal Research, in collaboration with the European Association of Research Animals. All the projects carried out at the facility of Aquaria and Experimental Chambers (ZAE, Figure 1) that include experiments with vertebrates (fish and frogs) and cephalopods follow the EU Directive that includes the publication of non-technical project summaries and the results of retrospective assessments. The projects need to comply with the national legislation, which establishes all the basic rules for the protection of animals used in experimentation and other scientific purposes, including teaching. It is compulsory for the personnel working at the ZAE to have the proper training and qualifications to carry out their duties with experimental animals, ranging from procedures to project design. Moreover, all the experiments need approval from the Committee of Ethics in Animal Experimentation at the ICM and the CSIC's Ethics Committee, which can formulate recommendations about ethical and deontological principles related to the research. Finally, the experiments are revised and approved by the local authorities, which issue an authorization number for the study. The ICM's commitment to animal welfare is crucial for a responsible use of animal marine models. Under the current research challenges, the use of animals cannot be fully omitted, although application of the 3Rs principle will ensure humane treatment. Indeed, animal models have been used to support scientific advancements in many marine research fields, particularly in fisheries and aquaculture such as reproduction, nutrition, disease, genetics and sustainability of marine living resources. The ARRIVE (Animal Research: Reporting In Vivo Experiments) guidelines were developed in 2020 with the aim of ensuring transparency, reliability and reproducibility in animal research. They consist of a checklist of 21 items –10 of them recently revealed as essential– that should be included in any study reporting on animal experimentation. However, although these guidelines have been endorsed by more than a thousand scientific journals, their implementation (particularly the information related to optimal environmental housing conditions) still needs to be improved.

The inclusion of guidelines for ethical methods to provide animal protection during experimentation will be important not only for ensuring an appropriate standard of welfare but also for maintaining public support for marine animal-based research. The ICM-CSIC is firmly committed to raising awareness of marine animal welfare and providing all the tools for protecting these experimental research models.

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3.7. The contribution of bivalves to coastal ecosystem services

Montserrat Ramón, Eve Galimany

Ecosystem services are the benefits that societies obtain from ecosystems. This concept originated in the 1970s and gained importance when the United Nations launched the Millennium Ecosystem Assessment in 2005 (http://millenniumassessment.org). The objective of this assessment was to analyse the consequences of change in ecosystems for human well-being and to foster actions to improve their conservation and sustainable use.

The coastal strip provides numerous ecosystem services related to habitat availability, including environmental education, leisure, provision of food and mitigation of climate change. The bivalve molluscs that live there are involved in important ecological processes that help improve our quality of life (Smaal *et al.* 2019).

Regulating services

Bivalves act as ecosystem regulators contributing to nutrient cycling, creating and modifying habitat, preventing coastal erosion and promoting biodiversity (Figure 1). The discharge into coastal waters of nutrients, especially nitrogen and phosphorus from land-based activities, is an important factor in the development of eutrophication, a phenomenon that triggers an increase in primary production and the degradation of water quality. Marine bivalves filter suspended particles and transform them into their own tissue and biodeposits (faeces and pseudo-faeces) that are transferred to the benthos. Thanks to this filtering capacity, they reduce the appearance of microalgal blooms and increase

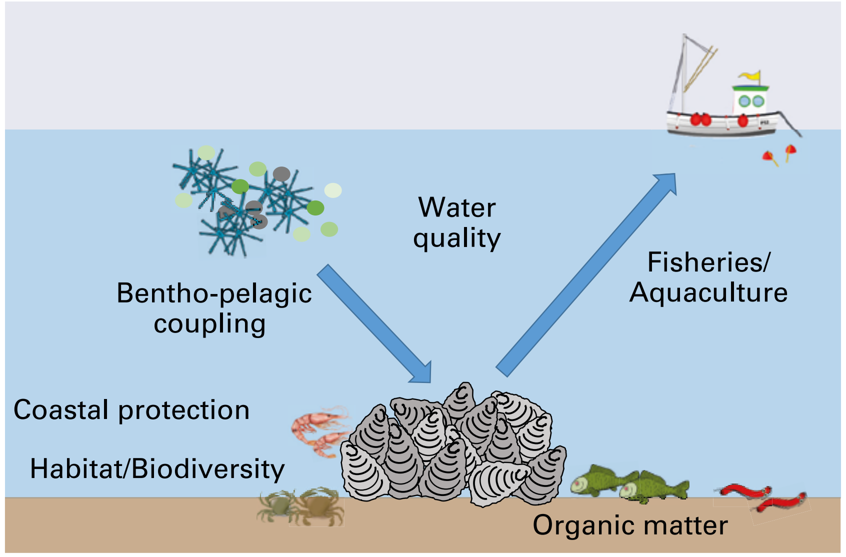

Figure 1. Diagram of the regulatory ecosystem services provided by bivalves.

Figure 2. Aggregations of mussels (*Mytilus edulis*) on the tidal flat of the Wadden Sea.

the transparency of the water, allowing greater penetration of light, which in turn favours the survival of phanerogam meadows. They also reduce the oxygen deficit caused by night-time respiration of phytoplankton and by sedimentation of phytoplankton blooms on the bottom. When the bivalve population is very dense, the transformation of phytoplankton and particulate organic matter into biodeposits can cause hypoxic or anoxic conditions on the bottom in areas with little water circulation. These wastes tend to have high concentrations of organic nitrogen which, once in the sediment, is used by denitrifying bacteria, thus promoting the mineralization and regeneration of the inorganic nutrients. The high capacity of natural and cultivated bivalve populations to extract organic particles from the environment is considered a nature-based solution (NbS) for mitigating excess organic matter in eutrophicated ecosystems and improving water quality in coastal areas (Galimany *et al.* 2017).

Furthermore, mussel aggregations and oyster reefs constitute complex three-dimensional structures that influence the morphodynamics of the bottom, the surrounding habitats and associated species (Figure 2). These biostructures help prevent coastal erosion and are biodiversity hotspots, harbouring high densities of invertebrates and providing shelter for juvenile fish.

Provisioning services

Bivalves also contribute to matter and energy outputs from ecosystems. Throughout history, molluscs have been present in the daily life of all civilizations. The first human groups that settled on the coast collected molluscs for food. Furthermore, shells used as tools, utensils and ornaments are often found at prehistoric sites. Molluscs provide a wide range of natural products based on both their meat and their shells. Their consumption is beneficial for health as they are low in fat and rich in protein, lipids and minerals (sodium, potassium, phosphorus, calcium, iodine, zinc and magnesium). Molluscs are one of the foods that contribute the most iron to our diet (4.5 grams per 100 of mussel meat) and are an excellent source of high-quality lipids because they concentrate omega-3 fatty acids. Fatty acid intake through consumption of bivalves is believed to have been critical for the development and evolution of the human brain (Crawford 2002). It should be noted that bivalves are at a low level in the human food chain, and their cultivation does not require the use of feed or medicine as they take advantage of the natural productivity of the environment in which they grow.

In addition to food, bivalves provide us with other direct benefits such as construction materials (aggregates) and jewellery. Some species, such as mussels, anchor themselves to hard substrates, secreting filaments called byssus. These filaments are covered by a protein cuticle that gives them good mechanical properties and great strength and adherence. Research into byssus has stimulated the development of adhesive biomedical materials for the reconstruction of human tissues.

Cultural services

Services of a third type provided by bivalves are non-material values that we obtain through use and enjoyment such as entertainment and aesthetic pleasure. Shell collecting is a widespread habit among beachgoers and collectors. However, this practice causes environmental damage, to the point that in some countries it has been prohibited. Like terrestrial gardens, "bivalve gardens" are a recent activity in which mussels and oysters are cultivated by a community for personal consumption. On the east coast of the United States, this practice has evolved from programmes to restore degraded estuarine systems.

Society is losing the benefits it derives from bivalves as their populations disappear from our shores. The decline of bivalve beds in the Mediterranean is caused by a combination of factors such as disease, overexploitation, pollution and loss of habitat (Baeta *et al.* 2014). To mitigate this loss, various initiatives are being carried out. The Native Oyster Network and the Native Oyster Restoration Alliance are interconnected networks for promoting the restoration of oyster beds in Europe. Such projects should be extended through the rehabilitation of the habitat, the sowing of juveniles from cultivation and efficient stock management programmes to recover the bivalve populations and continue enjoying their services.

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3.8. Towards monitoring and recovery of fishery-impacted species in deep-sea marine ecosystems: a joint effort between biology and technology

Jacopo Aguzzi, Joan Navarro, Maria Vigo, Ivan Masmitja, Nixon Bahamon, José Antonio García, Guiomar Rotllant, Laura Recasens, Jordi Grinyó, Marc Carreras, Joaquín del Río, Spartacus Gomariz, Joan B. Company

The oceans provide important ecosystem services, and protein provisioning is one of the main benefits for humanity. The millenarian Mediterranean fishing activity today accounts for almost half of all the fisheries in the EU, and the use of high-impact fishing methods has made this human activity one of the main drivers of ecosystem degradation, especially in demersal and benthic environments (Puig *et al.* 2012). Bottom otter gear (hereafter trawling) causes the removal of sediments and endangers demersal living resources and their ecosystems, with fragile epi-faunal species being replaced by mobile scavengers or predators and long-lived species being replaced by short-lived species. In the Mediterranean Sea, many commercial demersal populations are being overexploited, reducing the economic benefits of fisheries and the ecosystem services associated with cultural aspects of iconic species.

Given this situation, ecological networks of marine protected areas (MPAs), where no type of extractive activity is allowed (i.e. no-take reserves) and habitat connectivity is ensured with appropriate scales of geographic proximity, are being created (Vigo *et al.* 2021). Although the primary aim of MPAs is the conservation of nature, they also allow the recovery of fishing resources, including fragile sessile fauna, and habitat restoration.

Non-invasive ecological monitoring technologies

The development of non-invasive monitoring technologies such as underwater cabled video-observatories, mobile crawlers and stand-alone landers (Aguzzi *et al.* 2020) is increasingly required to evaluate the progress of habitats and the recovery of fish stocks in MPAs and surrounding areas, thus accomplishing the objectives of the Marine Strategy Framework Directive aimed to achieve Good Environmental Status. A suitable ecological monitoring technology operating remotely and autonomously (i.e. independent of human and vessel assistance) is expected to track changes in 11 descriptors as non-deviant from an undisturbed state, including biodiversity, alien species, fish stocks, food-webs, eutrophication, sea-bed integrity, hydrographical conditions, sea water contaminants, sea food contaminants, litter and energy.

Stand-alone platforms as a monitoring complement to oceanographic surveys

In the past few years, marine robotic approaches have increasingly allowed cost-effective, state-of-the-art monitoring of benthic and pelagic ecosystems remotely over diel, seasonal and multiannual scales. The technology of underwater cabled video-observatories acquiring multidisciplinary oceanographic and biogeochemical data without power and bandwidth constraints has been a key element for monitoring marine ecosystems (del Río *et al.* 2020). Spatially replicated data collection allows ecological indicators to be extracted, quantifying restoration efficiency, such as local species abundances and biomasses (by counting and sizing individuals) and biodiversity (by compiling species lists and their relative evenness). However, the study area is circumscribed to the deployment location, and the operation and maintenance cost of the underwater technology is considerable, therefore limiting its use. Moreover, fishery monitoring is being used to gather information about the biology of exploited species, but their management needs to include a whole ecosystem overlook in order to be effective (Aguzzi *et al.* 2020). To overcome these constraints, stand-alone platforms have been used as a complement to standard oceanographic cruises on board research vessels.

The role of autonomous underwater vehicles for ecological data collection

Recently, these deployments have been used in collaboration with Autonomous Underwater Vehicles (AUVs) (Figure 1). Whereas the use of AUVs for long-lasting remote deep-sea surveys is rare, an increase in their navigation autonomy and data collection and transmission capabilities may increase their appeal to broad marine explorations (Masmitja *et al.* 2020). Scientists and technologists are engaged together in the development of a spatially adaptive and non-invasive modular platform consisting of independent and wirelessly connected benthic stations and AUVs to monitor and map marine ecosystems during long periods under real-time supervision.

AUVs could play a central role in ecological and stock monitoring in a recently established network of no-take zones of the Spanish Mediterranean Sea (Figure 2). When associated with autonomous stand-alone landers, AUVs will allow the interpolation of biological and environmental indicators of individual no-take zones

Figure 1. The Girona 500 AUV used to track Norway lobsters (*Nephrops norvegicus*) at 400 m depth in the NW Mediterranean Sea.

that are scalable to the whole network, thus providing an overview of the ecological system areas. Landers and AUV modular monitoring networks have the potential to become a widespread solution for human impact assessment in very different contexts of revenue for the Blue Growth Agenda (i.e. advising stakeholders and policymakers on achieving clean, healthy and productive seas in the context of growing offshore and deep-sea maritime activities).

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Opening
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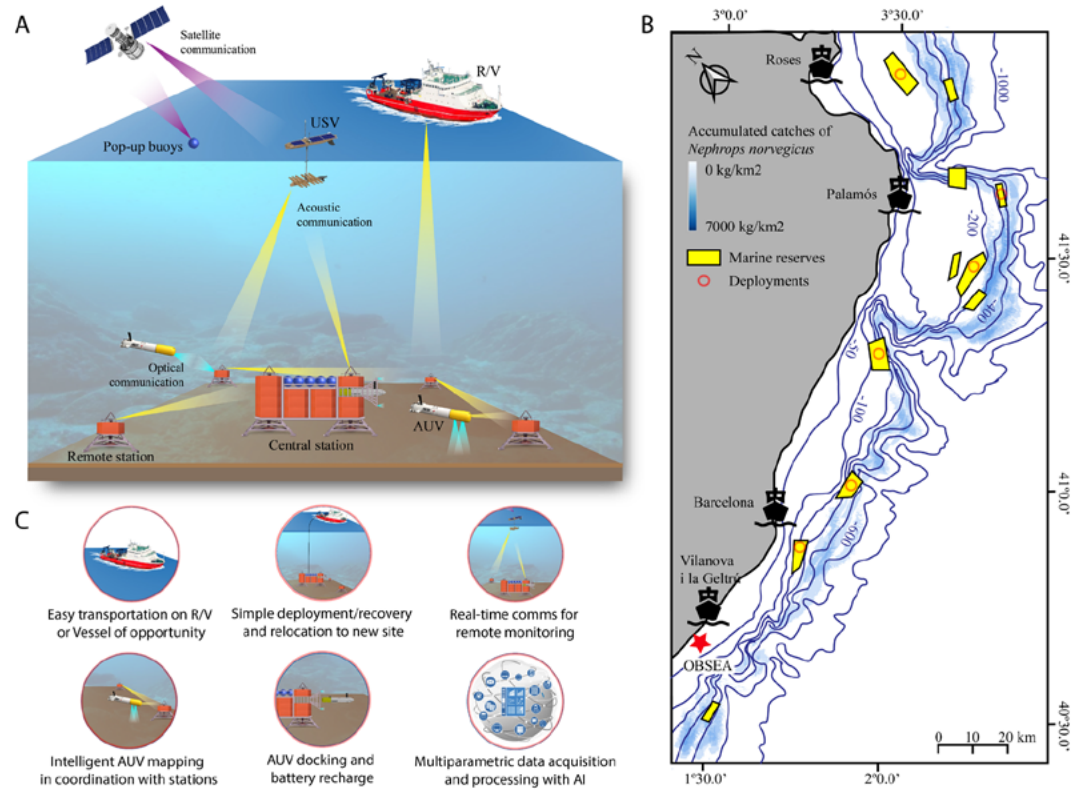

Figure 2. A spatially adaptive modular platform of independent and wirelessly connected benthic stations and AUVs (A) for intelligently observing, monitoring and mapping marine ecosystems during long periods with real-time supervision (B) and advanced key features (C).

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The ocean-atmosphere system
Physical basis of ocean primary
Phytoplankton in the Catalan Sea
Unicellular primary producers
Omics tools
Animal welfare
The contribution of bivalves
Fishery-impacted species
Science and living marine resources
The first fishing co-management in Catalonia

3.9. Science and living marine resources: towards a different future

Francesc Sardà, Isabel Palomera

The sustainability of exploited populations of marine resources has been extensively studied since the early twentieth century. The effect of the two world wars advanced population dynamics applied to fishing. When some fleets had to stop fishing during the wars, it was observed that fish populations were recovering from the exploitation they had suffered. This finding led to the development of models for scientific regulation of world fisheries based on the principles given by Hjort (1914) and others, and these models are still in use today.

Since then, these models have been applied to many seas and oceans around the world. They were applied in the Catalan Sea by members of the former Instituto de Investigaciones Pesqueras (CSIC) and have been applied continuously by members of the Department of Renewable Marine Resources of the Institut de Ciències del Mar (CSIC) in Barcelona. Since the 1970s, knowledge of Mediterranean fisheries has been advancing thanks to studies on the growth, reproduction, larval cycles, feeding and ecology of the main exploited species.

The role of Science

To determine the *maximum sustainable yield* that can be exploited annually from commercial populations of fish, crustaceans and cephalopods, it was necessary to find the *points of reference* for managing the fisheries. The appearance of digital technology during the 1980s led to the creation of precise tools for evaluating fisheries and working with a large amount of biological information and oceanographic data. Recently, the application of global production models has allowed fisheries to be seen them from an eco-systemic perspective (Coll and Palomera 1990). Through hard work and rigour, Spanish scientists predicted and warned of the over-exploitation that has led to the current collapse (Lleonart 1996). Currently, with a depleted fishery and failed management of a large part of the stocks, we must consider how a sustainable future can be achieved for these resources. We must consider how this unsustainable situation has been reached before deciding what needs to be changed (Sardà 2017).

Science is, by definition and by method, the most objective and intelligible way of anticipating uncertainty. The decisions made by national and international management forums on Mediterranean fisheries have not taken into account the results of scientific research and the warnings given by scientists (Cury and Miserey 2008), except on rare occasions such as the prohibition of fishing with trawl nets at depths of more than a thousand meters in the Mediterranean Sea.

The scientists' proposals for direct reductions of fleets and efforts, as well as other control measures, were seen as a hindrance to the socio-economic development of the sector in the short term. In Catalonia the result is clear: the sector has fallen to historical lows, with few catches and a catch per unit of effort that, despite the forced reduction of the fleet, has not yet recovered (Figures 1 and 2). This situation has been reached by giving preference to the economic performance of an already heavily subsidized sector and by applying policies aimed at voters instead of trying to achieve a sustainable fishery.

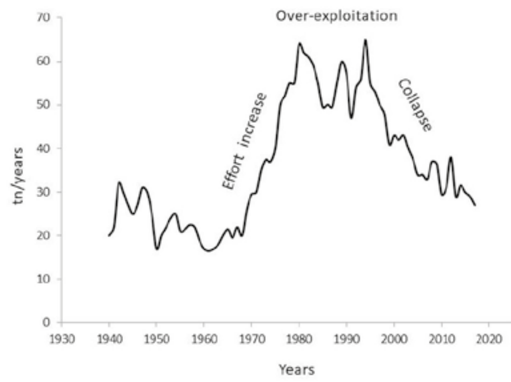

Figure 1. Historical evolution of total catches in Catalonia. The year 2020 was not considered due to the possible pandemic effect. Source: Servei de Pesca de la Generalitat de Catalunya.

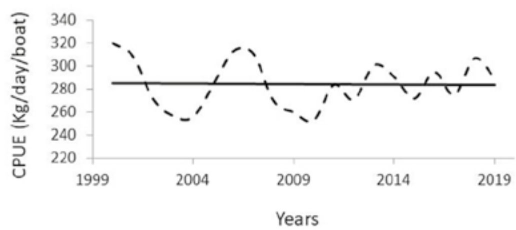

Figure 2. Evolution of catches per unit of effort (CPUE) in Catalonia since 2000 and trend line (horizontal). The year 2020 was not considered due to the possible pandemic effect. Source: *Servei de Pesca de la Generalitat de Catalunya*.

The short-sighted policy applied so far has not been effective. Measures such as reducing mesh size, reducing fishing time, limiting depth, closures and protected areas have not been sufficient to stop the current collapse, because they have been too timid to deal with fleets that are oversized in number and in individual fishing power, and because technological development has been uncontrolled and largely ignored. Furthermore, governments have failed to apply the scientific recommendations in order to avoid antagonizing the fishing sector.

What should be done?

The guidelines for recovery should be drafted under the leadership of scientists, with full independence and in representation of society and without interference from the sector or from governments. Of course, the fishing sector must be listened to so that the government can manage the technical, economic and social exploitation of the resource, but they should not act as a pressure group to influence technical and scientific decisions. Fishing licenses must be granted and guidelines must be established under strictly scientific criteria until a stable, high-quality public-private service is set up.

Scientists must determine how, when and in what way the resource is exploited to achieve the *maximum sustainable yield*. The government must negotiate with the sector how to adapt the fishery to the bio-ecological context, ensuring that maximum sustainable catches are not exceeded, resizing the fleet, managing closures, expanding protected areas, compensating for technological development, carrying out surveillance work and stopping economic disinvestment.

The "Tragedy of the Commons" (Harding 1968) explains that in a scenario of overexploitation of shared resources, if the users act individually and independently but rationally based on their own interest, they end up behaving contrary effects to the common interest and exhausting the resource they share. By "common", we mean any shared and unregulated or poorly regulated resource, such as the atmosphere, rivers and oceans, fish populations, forests and jungles. A good example of this is how the current global crisis caused by unlimited industrial development has been reached on the basis of burning fossil fuels, depleting mineral resources and destroying biodiversity, despite the knowledge that we live in a world of finite resources. Even the current COVID-19 pandemic has clearly taught us the predictive and resolutely value of science.

In order to attain a truly sustainable development of living marine resources, the great challenge we must face in the next decade is that of placing the recovery of these resources in the hands of independent scientists with binding powers of decision.

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3.10. The first fishing co-management in Catalonia: the case of the "sonso" fishery

Pilar Sánchez, Montserrat Demestre, Ana I. Colmenero

The sand eel fishery is carried out traditionally by 25 artisanal boats scattered around six fishing ports on the northern coast of Catalonia (Barcelona, Arenys de Mar, Blanes, Sant Feliu de Guíxols, Palamós and L'Estartit). The "sonsera" is a boat seine used to catch *Gymnammodytes cicerelus* and *G. semisquamatus* (Sabatés *et al.* 1990), known as "sonso". Individuals of both *Gymnammodytes* species are short-lived forage fish that rarely reach 15 cm length and live on shallow sandy bottoms (between 5 and 10 m depth), usually burrowing into the sand.

The "sonsera" can refer to both the gear and the boat (Figure 1). The capture of these sand eels is not possible with any other method because of the mesh size necessary to catch them and the depth of less than 50 m. The boats operate five days a week, going to fish early in the morning when the sand eels leave their holes. The fishermen search for sand eel schools using echo sounding, and after one to three hauls they return to port to sell the catch. Both sand eel species can appear mixed in the catch, which is entirely devoted to direct human consumption, because the species is highly appreciated in the region.

The problem

In 2006, the European Union adopted the first comprehensive regulatory framework concerning management and technical measures for Mediterranean European countries. One of the pillars of this regulation was a provision for the compulsory adoption by member states of management plans for some fisheries conducted within their territorial waters not later than December 2007. By the specific mention of boat seines, this provision directly affected the "sonsera". Moreover, the same regulation included technical measures related to mesh size, the minimum distance from the coast and the depths allowed for towed nets, which also have an impact on the fisheries. The mesh size for towed gears was established in July 2008, and the use of the gear was prohibited within three nautical miles of the coast although both technical measures benefited from a transitional derogation until the end of May 2010. Moreover, both measures might even benefit from a permanent derogation if it is duly justified by scientific evidence and in the context of a management plan. An indispensable additional requirement for vessels to obtain the derogation (the minimum distance from the coast) is to have a record of accomplishment in the fisheries of more than five years with no possibility of a future increase in fishing effort. This measure had a crucial impact on the size of the fleet targeting sandeel in the Catalan region, because it resulted in an effective closed list of 25 vessels allowed to fish for these species.

The management plan needed for the fishery to obtain the derogations was initially sent to the European Commission in 2010, and revised versions of the plan were sent in 2011. In January 2012, the plan was rejected due to the lack of a scientific study supporting the proposed measures and derogations. Therefore, the fishery was deemed illegal and forced to close, producing a huge crisis in the sector. The fishermen approached non-governmental organizations (NGOs), scientists and the administrations calling for support. In April 2012, a Sand Eel

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The first fishing co-management in Catalonia

Figure 1. Sonsera net (Foto: Alba Rojas).

Co-Management Committee composed of the administration, boat seine fishermen, scientists and NGOs was established for the first time as the legal entity responsible for implementing the management plan in Catalonia. The only authorized sand eel fishery is devoted to providing the necessary information to develop the management plan (Sánchez *et al.* 2013, Lleonart *et al.* 2014). Scientists of the ICM-CSIC carried out the research study requested by the EU Commission. After approval by the authorities, the management plan allowed the opening of the commercial fishery in the 2014 fishing season.

At present, the Sand Eel Co-Management Committee has several long-term objectives: to implement the plan, to control its implementation, to monitor the indicators, to adjust the fishing activity according to the harvest control rules and to decide on penalties for non-compliance.

The co-management

Why is co-management so important? Fisheries management through co-management transfers the responsibility to all stakeholders involved in sand eel fishery. Under this innovative approach, management measures, including monitoring and control measures, are jointly designed by the stakeholders. The full participation of the fishing sector in the decision-making process is particularly important because it ensures their proactive participation and genuine commitment to sustainability (Nielsen *et al.* 2004). This commitment is crucial in providing a real incentive for a thorough adherence to the management rules. The approach also recognizes the social and cultural values of the fishing sector and therefore their long-standing tradition, which is particularly important in coastal regions (Castilla and Defeo 2001).

The Sand Eel Co-Management Committee received the World Wildlife Fund Award for Conservation Merit in 2013.

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Photo: Josep-Maria Gili

4. Predictable ocean

Marta Coll, Carolina Gabarró, David Casas

Global change, climate crisis, sustainable growth, economic decline, blue growth, green deal, collapse… all are common words present in all social and scientific forums. They are concepts that configure the current framework where all alerts have been triggered, they are real warnings for our survival. These words evidence that we are facing huge challenges ahead of us involving economic, social and ecological components of our activities.

Earth Systems have complementary roles contributing to the healthy Planet and the equilibrium that we need. In this context, the Ocean is a major actor. For example, around 40% of the world's population lives in coastal areas, the ocean regulates the climate and produces part of the oxygen we breathe, and key marine habitats as well as the seafloor are large carbon sinks.

All geological, physical, biochemical, and ecological processes are intimately related and small changes in one variable are important for understanding net changes that are occurring in the whole oceanic system. The large uncertainty about how the ocean functions requires continuing a major scientific endeavour: the generation of key knowledge needed to advance our capability to predict future ocean dynamics.

In this context, it is essential to enhance exploring and understanding the elements that control changes in the ocean, and their relationships with the atmosphere and cryosphere, particularly in relation to climate change. This required knowledge that ranges from the coastline to the abyssal plains, including past, current and future ocean conditions, and from the smallest to the largest organisms.

A predictable ocean will allow society to get adapted and respond to its changing conditions. A comprehensive understanding of the interconnections in ocean processes will enhance the predictions which are necessary for a resilient society facing the challenges ahead.

4.1. From sea up: oceans, air, clouds, and climate

Rafel Simó, Martí Galí, Manuel Dall'Osto

"Where is the water of Kane? There on the ocean, in the driving rain, in the heavenly rainbow, in the rising mists, in the blood-red rainfall, in the ghostly cloud-form; there, is the water of life." (Sinclair 2019).

Polynesian sailors have been looking up for millennia to find their way in the ocean desert. They read the stars, the flight of the birds, the shapes and colors of the clouds, because they know that the sea and the sky are so inseparable that one cannot be explained without the other.

Oceanographers also have plenty of reasons to look up. From the atmosphere comes most of the energy that mobilizes the sea and life, both in the form of light and heat from the sun, as well as mechanical energy transmitted by the wind. Air also supplements some essential elements for life, such as iron or nitrogen; and unfortunately, it also carries pollutants of all kinds. At the same time, the atmosphere receives the breath and the beat of the sea. It has already been amply demonstrated that we can understand neither the composition nor the dynamics of the atmosphere if we do not understand the influence the oceans exert on them: they take in, transport and return heat and greenhouse gases, they supply most of the water vapor, and emit substances that regulate atmospheric reactivity and optical properties (Brévière *et al.* 2015). Since all these processes are fundamentals of climate, we can say that the oceans are an essential player in climate regulation.

The breath of the living ocean

This impact of the oceans on the atmosphere and climate is greatly enhanced by the presence of life. What would otherwise have worked based on simple processes of exhalation and dissolution, evaporation and precipitation, splashing and deposition, photochemistry and energy exchange between different fluids, life makes it a complex network of metabolites, nutrients, excretion waste, recycling, detritus. The breath of a dead sea would be mainly vapor, salt, carbon dioxide and oxygen, and that of the living ocean adds sulfur, nitrogen, iodine and bromine gases, organic compounds –most still unknown–, viruses, bacteria, and cellular debris (Simó 2011). Some of these substances exhaled by the sea are involved in the chemistry of the atmosphere, to make it more or less oxidant, more or less acidic, or to participate in the destruction of ozone. Others return important elements from the sea to the continents that otherwise the continents would lose due to permanent washing by the rain. Other substances form atmospheric particles, aerosols, which are involved in the optics of the atmosphere and, therefore, in the energy balance of the planet (Figure 1). Deciphering the breath of the sea and what regulates it is one of the most formidable challenges in marine and climate sciences for the years to come.

Aerosols and climate

Aerosols have always aroused scientific interest, but this interest has multiplied in recent years. In large part, because breathing well, efficiently and healthily, is one of the functions we need most. We do not see aerosols, airborne dust, the way we see dirty water and garbage, but we know they carry pollutants, allergens, and disease vectors. That's why measures are

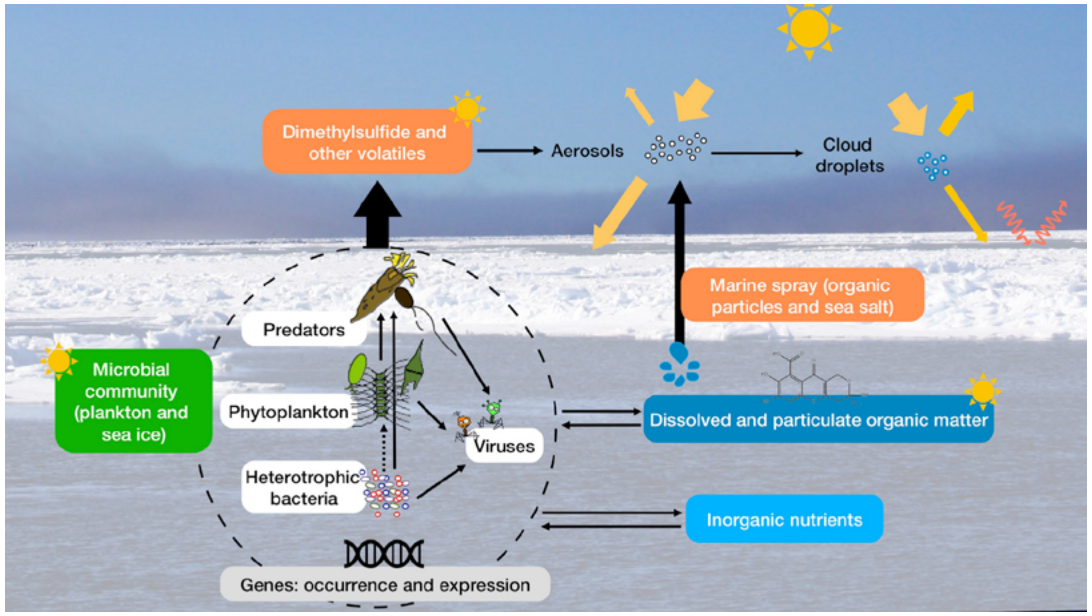

Figure 1. The breath of the sea: besides exchanging heat, CO_2, O_2 and water vapor, the oceans emit into the air substances that intervene in atmospheric chemistry, in particle (aerosol) formation, and as seeds for cloud condensation. Many of these substances are produced by plankton and, depending on the ecosystem, also by life-colonized sea ice, animal excretions, and riverine outflows.

being implemented to improve air quality in the environments in which we live and work. That's why we constantly learn about how aerosols form and transform. The climate crisis has also helped increase interest in airborne particles. The IPCC recognizes aerosols as the main source of uncertainty in global warming projections. This is because they are a very powerful climatic agent; in fact, they are a climate-cooling agent. On the one hand, they darken the air, albeit imperceptibly, because they absorb and disperse solar radiation; this effect, called the direct effect, seems to be diminishing with the decrease of dark aerosols of human origin as we turn into more efficient and clean combustions. On the other hand, aerosols also have an indirect climate effect, which is even more important: they are indispensable in the formation of clouds (Brooks and Thornton 2018). Since the late 19th century, we have known that for water vapor to condense and form clouds, not only saturation conditions are needed but also particles that act as "seeds" around which droplets form, the so-called *condensation nuclei*. It is no secret that clouds cover a third of the Earth's surface, reflect and filter solar radiation, and while they also trap the heat radiating from the planet's surface, altogether they are the main cooling factor of the climate, especially over the oceans; understanding their formation/disappearance cycle is one of the most coveted pieces of the climate modeling puzzle. Because a cloud formed over more condensation nuclei is cooler and lasts longer, we already have another good reason to investigate oceanic aerosols, how they are, where they come from, what regulates them, how they become good cloud condensation nuclei, how they respond to climate change.

The rapid development of instruments for measuring the abundance, size distribution and chemical composition of aerosols is making it possible to describe them in the cleanliness of marine air. We know that two components predominate: the salt crystals raised by the wind with the splashes, the foam and bubble bursting, and the sulfur from plankton activity. Salt is part of what we call *primary aerosols*, which incorporate into the air already as a particle. Along with salt we find sugars, proteins, and whole cells. Conversely, sulfur is the main component of *secondary aerosols*, those that arise from the conversion of gases into particles and grow by reaction and condensation of more gases. It is accompanied by carbon, nitrogen and iodine compounds. In the most recent studies, we seek to follow the birth of marine primary and secondary aerosols and determine their ingredients (Brean *et al.* 2021). Simultaneously with the research on aerosols, we bring into play the knowledge acquired in the study of the genetics, physiology and ecology of plankton in order to understand the biological processes underlying the formation of marine aerosols. With all this information, we intend to develop numerical models for predicting aerosols and clouds. While these models are just under construction, statistical approaches with orbital satellite data offer us shortcuts to turn the results of our local observations into regional and global patterns (Galí *et al.* 2019). Ultimately, the goal is to decipher whether the living oceans, with their natural exhalations shaped over millions of years, have the capacity to dampen global warming.

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4.2. Deciphering the recurrence of marine sedimentary processes

Belén Alonso, David Casas, Gemma Ercilla, Ferran Estrada

Sedimentary processes have been part of the history of our oceans throughout geologic time. These processes have been the same for several million years, forming a wide but limited range of events that are repeated at frequencies depending on the dominant geological framework. The recurrence of sedimentary processes depends on whether they are tied to steady conditions, convulsive geologic events, extraordinarily energetic events of regional influence (e.g. explosive volcanic eruptions, giant mass failures, catastrophic floods, major earthquakes and giant tsunamis), cyclic sea-level and climate changes or tectonic pulses. Here, we present the way that geologists approach cyclicity and recurrence and we formulate some research questions.

Why do we do it?

The recurrence of marine sedimentary processes (e.g. mass-flows, turbidity flows, bottom currents flows and faults) must be deciphered in order to understand the geological evolution of the continental margins and basins and to identify the potential geological hazards that these processes may represent. To tackle this problem, marine geologists have to decode the sedimentary records preserved in the seafloor and in the

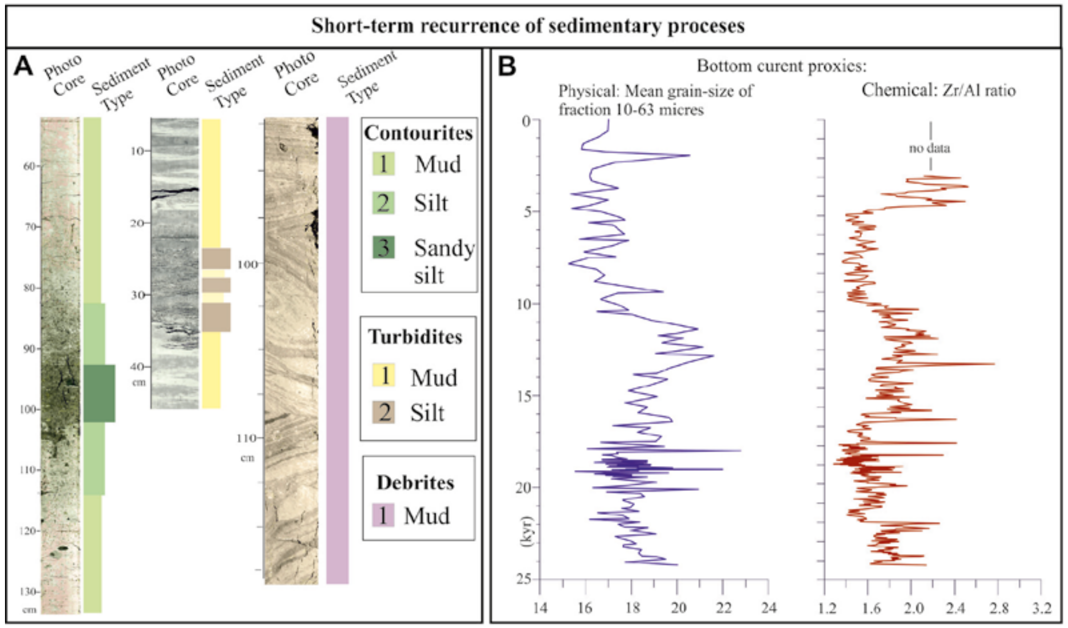

Figure 1. A, sediment cores showing three types of sediment (contourites, turbidites and debrites; modified from Alonso *et al.* 2016). B, sediment core showing the high recurrence of palaeo-bottom current changes during the last 25 kyr.

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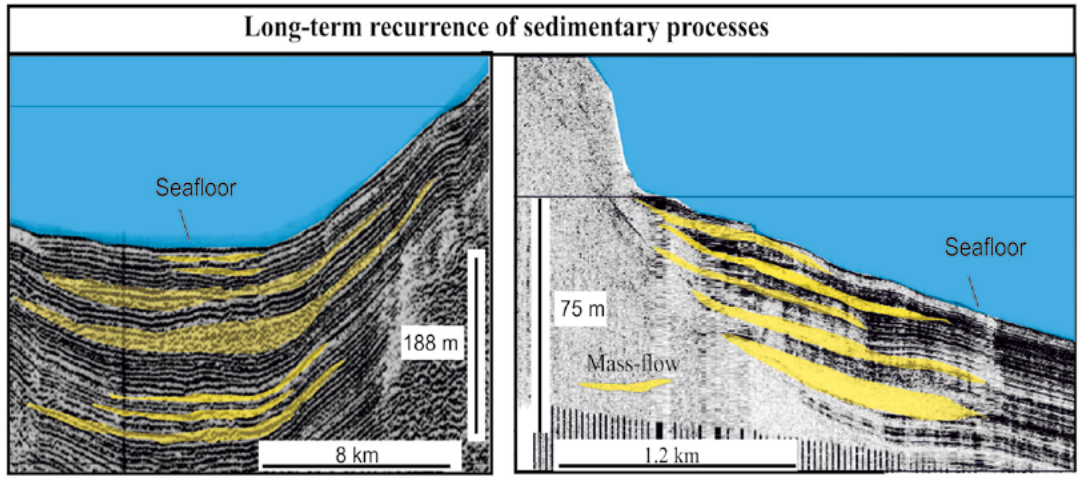

Figure 2. Seismic profiles displaying the recurrence of mass-flows during the Quaternary (2.6 Ma) in the SW Mediterranean (modified from Alonso *et al.* 2014).

physiographic domains of continental margins (shelf, slope and rise) and basins.

How do we do it?

Knowledge of the sedimentary record is mainly achieved by studying seismic profiles and sediment cores (Figures 1, 2). Both are essential tools for defining the stratigraphic and sedimentary framework, determining which deposits are older, how they are laterally related to other deposits and how their characteristics (e.g. composition) change. In order to decipher the recurrence of sedimentary processes, it is necessary to know the chronology of the geologic events. There are two approaches for doing so: direct and indirect. The direct method consists in quantifying the age of sediment samples through accelerator mass spectrometry radiocarbon ages and oxygen isotope records (Figure 1B). The indirect method determines the age of sedimentary deposits recorded on seismic profiles by identifying and correlating seismic boundaries (horizons) with the calibrated ages of sediment cores. Other invasive tools (sampling for sedimentology, chemistry and mineralogy) and non-invasive tools (e.g. multi-sensor core logger, X-ray fluorescence scanning, X-ray images, X-ray computed tomography and photographs) working at different resolutions are also important for interpreting sedimentary processes and calculating their recurrence.

The use of sedimentary records, seismic profiles and sediment cores, provides information at two timescales: thousands to hundreds of years (Figure 1B) and millions of years (Figure 2).

What is the recurrence of sedimentary processes on the Iberian Margins?

The frequency of triggering of mass-flow events in the Alboran Sea has been estimated to range from medium (one event every ~40 kyr) to low (one event every ~300 kyr). A medium frequency of mass-flow events predominates throughout the Quaternary (2.6 Ma to present); Figure 1; Alonso *et al.* 2014). This recurrence is closely linked to tectonic/earthquake pulses defining the evolution of the eastern Alboran Sea. The sediment source of turbidite flows is usually linked to sediment transport from rivers to submarine canyons during sea-level falls or from the continental shelf to canyons during sea-level rises and highstands. The frequency of events is therefore highly variable, sometimes with patterns driven by sea-level cycles of 400, 200 or 100 kyr. In another geological context, the deep oceanic environment of the Galicia Bank, where no influence of river discharge occurs, moderate recurrence of turbidity flows has been described: up to one event every 3 kyr (Alonso *et al.* 2008).

Other geological processes linked to oceanographic dynamics such as bottom currents are subject to the variability and rates of water mass changes. High and moderate frequency of palaeo–bottom current changes have been detected in the western Mediterranean (one event every 1.9, 2.3, 4.0 and 6.2 kyr; Alonso *et al.* 2021). These events are potentially linked to both oceanic and solar forcing mechanisms, which impinge on the deposition of contouritic deposits where these changes are recorded (Figure 1B).

Earth and the oceans are in constant evolution, and geologic time involves an enormous number of years from a human perspective. Even considering the huge range of time that could be involved in the construction of a particular sedimentary system, the emergence of instant geological events, even on a human scale, is not only possible but has a probability that should not be neglected.

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4.3. Mapping the seafloor: resolution is the solution

Ferran Estrada, Gemma Ercilla, David Casas, Belén Alonso

The predictability of the ocean floor is part of one of the great achievements pursued by the Decade of Ocean Science for Sustainable Development and has been one of the main targets for the Institut de Ciències del Mar throughout its 70 years of history. The cartography of the seafloor is a key element for understanding the past, present and future of underwater geological processes and therefore achieving a predictable ocean. This achievement is still far from being a reality, since much of the ocean floor still remains unexplored or its knowledge is limited to low-resolution images. Resolution has been the solution for understanding the dynamics of sedimentary processes and tectonic structures. This is because it has allowed us to map previously undiscovered features and improve our previous interpretations with stronger and more confident morphological interpretations. The detail of our observations (closely linked to technological development) and the better understanding of geological processes enhance modelling and improve predictability.

Bathymetric images of the seabed: from low to very high resolution

The accuracy of geomorphologic measurement is a function of the data relative to the scale of the target. In many cases, it may be possible to make reliable measurements of first-order morphometrics using relatively coarse-resolution (often hull-mounted) multibeam data. Examples of first-order elements are the total length or the main channels and lobes of a turbidite system, major faults and folds, large-scale contourite features and the presence of landslides. However, many small features will be missed using such coarse-resolution data, and more detailed measurements of key elements are often not feasible, such as bedforms indicative of local currents, detailed morphometry of a landslide to establish the processes involved and the identification of fault-derived sedimentary wedges to identify relative periods of recurrence.

To illustrate the fact that resolution is sometimes the solution, see Figure 1, which shows three images of different detail (resolution) of the same area of the slope on the Garrucha continental margin, near Cabo de Gata, Almería, SE Spain. The image with the lowest resolution (Figure 1B) is made of a grid of 667×667 m (General Bathymetric Chart of the Oceans [GEBCO] database); the second (Figures 1A and C) is made of a grid of 50×50 m (hull-mounted multibeam data); and the third (Figure 1D), made of a grid of 1×1 m, was recorded close to seafloor from an autonomous vehicle (multibeam bathymetry). In each case, if the dimension of a given geological structure is below the resolution used, it will go unnoticed by us and our interpretation will therefore be biased. In practice, the approach to the resolution problem is mainly a matter of balance between time and space, that is, availability of ship time versus the area of the seafloor to be investigated. The greater the detail, the smaller is the investigated area. This is because we commonly recognize the main geological characteristics of the area to be studied at low resolution, prioritizing the size of the area covered to the detriment of resolution. Once potential targets have been recognized, the area investigated is reduced for the sake of resolution.

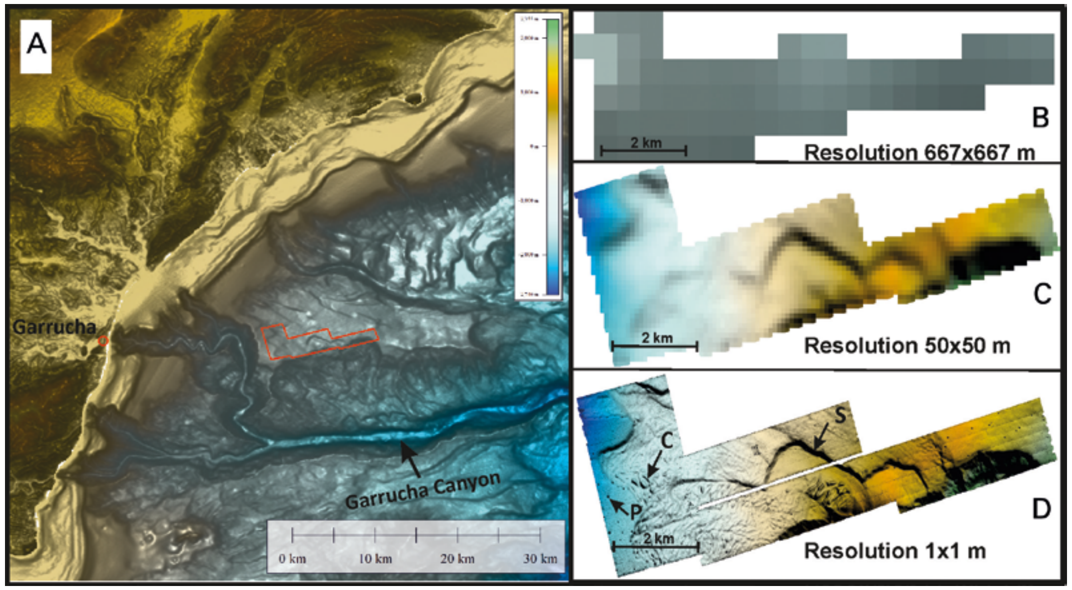

Figure 1. Our interpretations are dependent on data resolution. A, bathymetric map (50x50 m) of the Garrucha Canyon, Almería, Spain. The red polygon bounds the zoomed bathymetry; B, GEBCO database (grid resolution 667×667 m); C, hull-mounted multibeam bathymetry (50×50 m), the FAUCES project; and D, autonomous vehicle multibeam bathymetry (1×1 m). Note the small, rounded depressions of fluid scapes (pockmarks, p), only observed in the autonomous vehicle bathymetry (D); crests (c) related to slide blocks; and scarps (S) related to slide scars not identified in the GEBCO database.

High resolution of marine geological research: a social demand

As knowledge has increased on underwater geologic processes that can affect populations and their infrastructure, in addition to those of economic interest and those involving basic science, predictability has become a social demand requiring high-resolution geo-marine studies.

Some examples carried out at the ICM are related to types of slope failure affecting the seafloor and whether or not they remain active (Casas *et al.* 2011). Detailed structural analysis has made it possible to model the tsunami associated with an active fault in the Alboran Sea and to verify the propagation model, the affected coastal areas, the height and velocity of the wave, the time of arrival and the inundation area (Estrada *et al.* 2021). The understanding of submarine valley dynamics and their complex hierarchy have allowed us to offer new insights into the characteristics of the passing turbidity flows and to establish analogous models to compare (predict) with other areas (Ercilla *et al.* 2002, Estrada *et al.* 2005). The detailed mapping of the extensions and lateral changes between contourite drifts and of contourite terraces have been essential for decoding the circulation of water masses and characterizing their near-bottom layers sweeping the seafloor.

"Resolution is the solution" is an important strategy with a view to the Decade of Ocean Science for Sustainable Development. The cases put forward in this text are some examples of a great variety of studies carried out at the ICM, but we must not forget that the future task facing us is enormous and will require a common effort from the scientific and technological community to achieve a better understanding of geological processes that will allow us to model and predict them.

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4.4. *Mare salis intellegere*. Knowing the salt of the oceans

Nina Hoareau, Mikhail Emelianov, Joaquim Ballabrera, Carolina Gabarró, Verónica González-Gambau, Maribel Lloret, Estrella Olmedo, Marcos Portabella, Jordi Salat, Joaquín Salvador, Marta Umbert, Antonio Turiel

In 1987, Konstantin Fedorov, a prominent Soviet oceanographer of the time, dedicated one of his popular science talks to the salinity of the ocean and called it "The Cinderella of Dynamic Oceanology". Fedorov said that "The fate of salinity as a physical parameter is closely related to the dynamics of ocean waters and is very similar to the fate of poor Cinderella in Charles Perrault's fairy tale. And, like the fate of poor Cinderella, salinity has long cried out for justice".

In fact, historically, salinity observations have been less valued than other physical parameters of the ocean, such as temperature, currents, waves or sea level.

Salinity has traditionally been measured by oceanographic surveys, starting with the Challenger Expedition between 1872 and 1876 and was later also measured from fixed stations. While, systematic measurement on a global scale began with the first Argo profilers in the 2000s and continued with the launch of the Soil Moisture and Ocean Salinity (SMOS) satellite dedicated to measuring surface salinity from space (Font *et al.* 2012).

Why is it necessary to measure salinity?

Salinity is a fundamental ocean variable. Together with temperature, it contributes to the determination of density, which modulates the intensity of mixing processes in the upper layer of the ocean and the formation of water masses and currents.

The main processes that influence salinity variability are related to water exchanges between the ocean and the atmosphere (evaporation and precipitation) and to advection. If we look at a map of surface salinity or a transect of the Atlantic Ocean from north to south, we see that salinity varies from one place to another (Figure 1), with values that are generally between 32 and 38 in the open ocean. However, it has been observed that the concentration of salt in the oceans does not show great changes on a climatic scale, and its average value is 35.

Surface salinity is influenced by runoff from rivers near the coast and by the mechanisms of formation and melting of sea ice in polar areas. This formation of sea ice contributes to the formation of deep waters, the main forcing of the general thermohaline circulation. All this, together with evaporation and precipitation, modify the surface salinity, which allows it to be used as a tracer of of the water cycle. Moreover, since salinity is only modified on the surface, it is used together with temperature as a tracer of water masses.

How to measure salinity?

One of the main observations of the first world oceanographic expedition, the Challenger Expedition of 1872–1876, was that "salinity varies from one sea to another, but the relative proportions of the salts that compose it are maintained". Thanks to this key observation, measuring the concentration of a single component of the salts contained in seawater makes it possible to recover the concentration of the others, and therefore the salinity. And until the first part of the 20th century, salinity (expressed in parts per thousand: ppt or ‰) was estimated by chemical methods from the chloride content, the largest component of dissolved salts in seawater (Knudsen 1901).

In the 1940s, it was observed that, at a fixed temperature, the electrical conductivity of seawater depended on salinity, which is why the chemical method has been replaced by the measurement of conductivity at a fixed temperature. This method led to the arrival of new instruments: salinometers. From here, the salinity of a sample was set as the conductivity ratio at 15°C between the sample and a standard corresponding to a salinity of 35 ppt, so this new scale (practical salinity of 1978; PSS-78 o PSU for pratical salinity units) no longer has units. Finally, in 2010 the concept of concentration was returned with absolute salinity in g kg^{-1} (TEOS-10). What makes salinity in the literature found in the diverse units.

And for the late 1960s until today, instruments have been developed to include a temperature and pressure sensor together with the conductivity sensor. The famous conductivity-temperature-depth (CTD) is capable of continuously measuring vertical or horizontal temperature and salinity profiles. Based on this technology, thermosalinographs installed in ships were developed to provide continuous measurements of surface temperature and salinity during navigation. Most of these instruments have been commonly used during oceanographic surveys since the 1970s, but they are also used on moorings, fixed stations or drifting buoys, such as L'Estartit ICM mooring or the ICM buoy (Salvador *et al.* 2010) designed at the Institut de Ciències del Mar (ICM-CSIC).

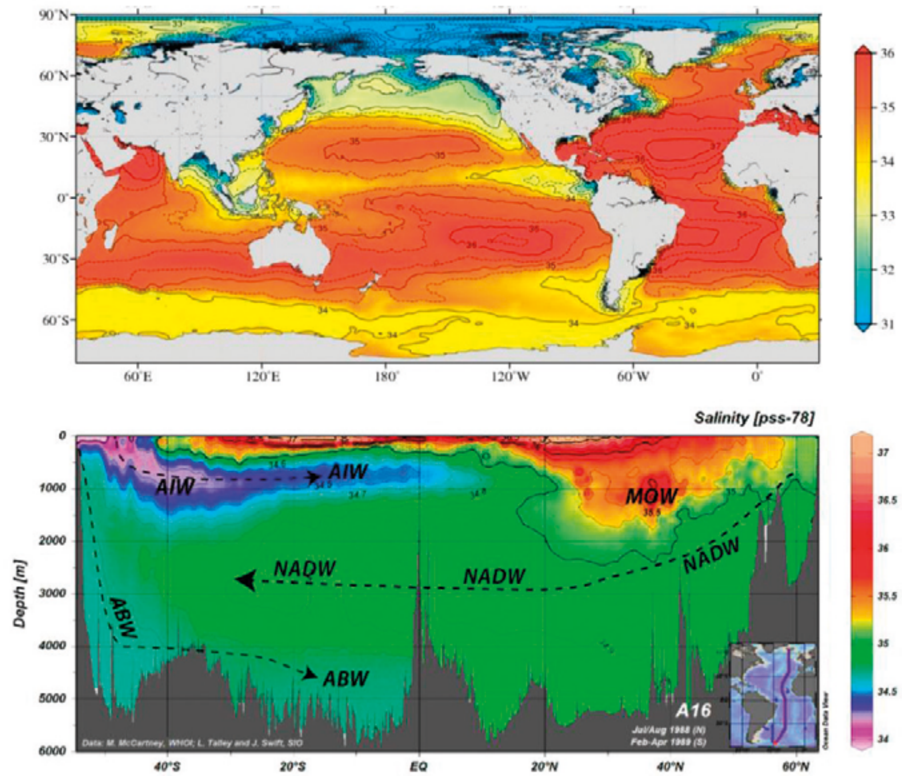

Figure 1. Above: annual mean surface salinity (World Ocean Atlas, 2018). Bottom, salinity transect in the Atlantic Ocean, indicating the main water masses: Antarctic Bottom Water (ABW), Antarctic Intermediate Water (AIW), North Atlantic Deep Water (NADW) and Mediterranean Outflow Water (MOW).

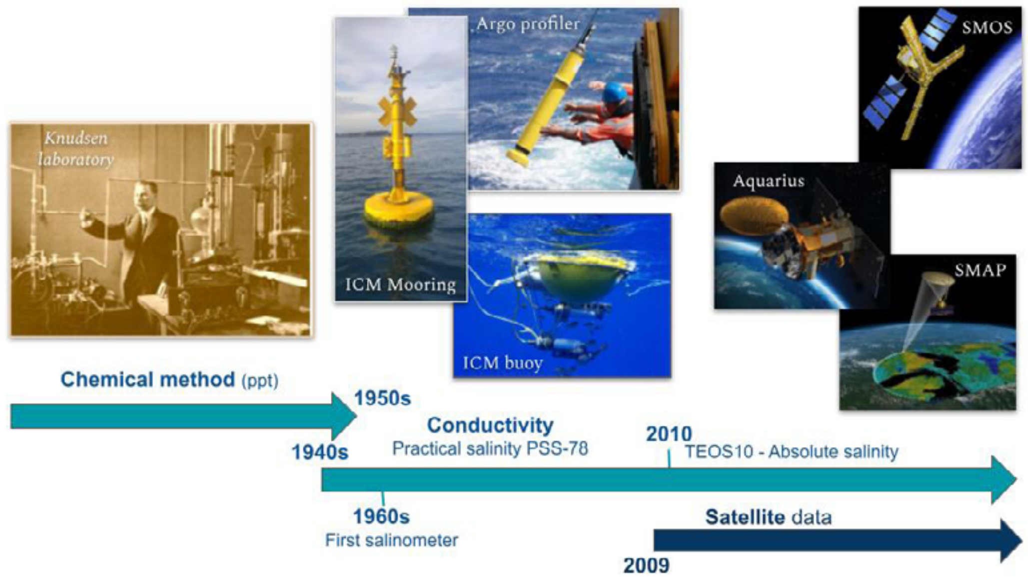

Figure 2. Chronology of sea salinity measurement methods. Photos from left to right: Martin Knudsen (1901); instruments based on CTD technology; the SMOS, Aquarius and SMAP satellites.

In order to measure salinity systematically all over the world, the scientific community started the international Argo programme in the early 2000s that performs routine measurements in the water column, providing continuous monitoring of the oceans through some 4000 active authomatic Argo profilers.

In parallel, techniques were also perfected for measuring surface salinity from space. A new generation of L-band (1.4 GHz) satellites arrived 40 years after the first oceanographic satellites (1970s). SMOS was the first satellite designed to measure surface salinity. It was launched by the European Space Agency in 2009, in collaboration with several European institutions, and the Barcelona Expert Centre of the ICM-CSIC led the scientific part. Today, with the subsequent arrival of NASA's Aquarius (2011–2015) and SMAP (2015) missions, more than ten years of surface salinity data are available.

At the end, thanks to the continuous efforts of the scientific community, the Cinderella of salinity has finally achieved its deserved importance, resulting in a wide range of instruments available to measure salinity at various scales (Figure 2). Today salinity observations continue to increase in all oceans including the polar areas, which despite their influence on the climate remain poorly studied.

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4.5. Microbial observatories: sentinels of global change

Ramon Massana, Dolors Vaqué, Maria Montserrat Sala, Josep M. Gasol

The biosphere has always undergone changes brought about by alterations in the geological substrate and the climate, and by the emergence of species with new functions and interactions. However, today we find ourselves in a unique scenario, in which a single species, humankind, is drastically and rapidly threatening all ecosystems. To deal with this situation, we need tools to track natural systems, understand changes at different time scales, document the current status and apply models to predict the future. This knowledge will be essential for proposing strategies aimed at mitigating anthropogenic changes.

Because of its extent and its volume of water, the sea is a crucial component of the Earth system. It was where life originated and diversified and today it contains an enormous biodiversity. Human societies have established a close relationship with the sea, which provides food, hosts maritime transport, and has become an attractive leisure space. The sea is also under the influence of global change, with challenges such as warming, acidification and pollution. Marine microorganisms, invisible but ubiquitous, are also affected (Hutchins and Fu 2017). Since they divide very quickly, they can act as sentinels of these changes, and this justifies the need for microbial observatories.

Microorganisms as sensors of the marine environment

Marine microorganisms develop a wide range of metabolic reactions that, because of their high biomass and rapid growth, have global implications. They participate in biogeochemical cycles, are the main primary producers in the sea and sustain marine trophic webs. They are also bioremediation agents and a little-explored resource of compounds for biotechnology and biomedicine. In addition, microorganisms can be indicators of the state and resilience of the ecosystem, as each species usually has different environmental tolerances. In the face of sudden changes, the taxonomic composition of the community may change, and they may be replaced by species better adapted to the new conditions. When there are subtle changes, such as the slow and continuous rise in temperature we are experiencing, they may also be replaced or they may gradually adapt. The consideration of microorganisms as actors in marine ecosystems is relatively new: in the 1970s they were seen to be very abundant, in the 1980s to be very active, and in the 1990s to be very diverse. Recently, the new techniques of massive DNA sequencing have allowed the taxonomic and functional diversity of marine microorganisms and their variability to be studied (Pedrós-Alió *et al.* 2018). Today there are a range of omics tools that allow us to determine in detail the species composition of a microbial community, the genetic capacity of the organisms that make it up, the genes they express at any given time and the compounds they produce.

The time scale in marine observation

The temporal study of marine organisms is not trivial. Achieving repeated biological sampling is laborious because it requires specially equipped oceanographic vessels. Oceanographic campaigns are unique events of limited duration with a mainly spatial dimension. The first global oceanic expeditions took place in the 18th and 19th centuries, including that of the Beagle with Charles Darwin, and recently there have been the Malaspina and Tara Oceans circumnavigations. For temporal studies, the stations ALOHA (Pacific) and BATS (Atlantic) have made a very important contribution by carrying out a monthly oceanographic campaign in the oceanic gyres of the northern hemisphere from nearby islands since 1988. Initially conceived as ten-year efforts, these initiatives have continued and they are now reference stations (Karl and Church 2014). In coastal systems, temporal sampling is more practical because of the proximity, and several oceanographic institutes have established a nearby temporal sampling station. On the Catalan coast, the efforts made by Josep Pasqual in L'Estartit, which began in 1969, have generated the longest record of water temperature in the Catalan sea. From these coastal stations we collect seawater samples to make exhaustive studies of the inhabiting microorganisms that are our sentinels of global change.

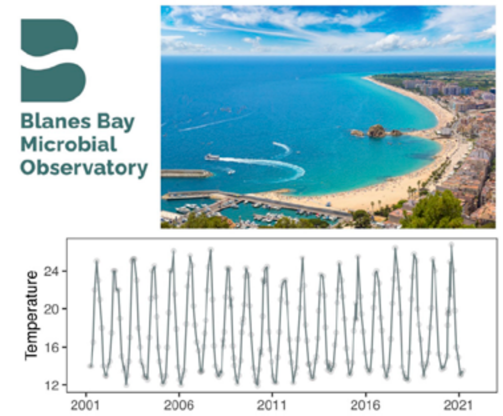

Figure 1. Blanes Bay, the site of BBMO sampling, a system with strong seasonality exemplified by the water temperature taken monthly for more than 20 years.

The Blanes Bay Microbial Observatory (BBMO)

The Blanes Bay (Figure 1) was one of the first places of research by the pioneering ecologist Ramon Margalef, and it has been the scene of many later studies. In 2001, a monthly sampling of microbial diversity began, first linked to specific research projects and later established as an indefinite observatory. The BBMO has a strong microbial focus and determines the abundance, diversity, activity and genetic potential of planktonic viruses, bacteria, archaea and protists (Gasol *et al.* 2016). The most important part of this effort is that, from the beginning, it collected genetic material of the microbial community, even before it was known how

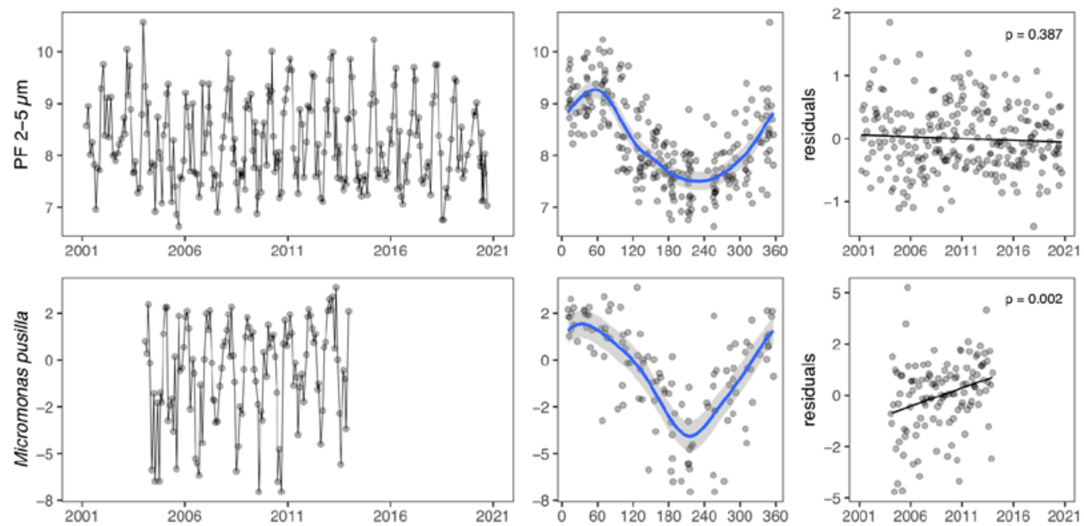

Figure 2. Seasonality and interannual trends of photosynthetic protists (PF) and *Micromonas pusilla*. Left, measured abundances. Centre, abundances in a year and their adjustment. Right, dynamics of residual values.

to process it (in 2001 molecular studies were still limited). The advent of massive DNA sequencing made it possible to exploit this genetic material. This twenty-year series allows us to study the seasonality of temperate systems and long-term interannual trends. As an example, we use microscopy to analyse the abundance of a microbial group, photosynthetic protists of 2 to 5 µm in size, and the relative abundance of the most important species in the group, *Micromonas pusilla*, determined by sequencing environmental DNA (Giner *et al.* 2019) (Figure 2). The two variables have a marked seasonality, observed both in the repetitive annual peaks and in the representation of all values in a single year, with a maximum in winter. The interannual trends, expressed by the dynamics of the residuals (the measured value minus the estimated value) show no changes in the first measure and a significant increase in the second. In addition to determining temporal trends, the BBMO has provided microbial communities for experimentation and isolation, and has appeared in more than one hundred published articles. It has become an international benchmark for the study of diversity and genomics of microorganisms that, though they are invisible, are extraordinarily important for the maintenance of healthy marine ecosystems.

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4.6. Turbulence and plankton dynamics in a warmer ocean

Miquel Alcaraz, Marta Estrada

Differences in the temperature and salt content of the water, which determine its density, wind energy and the rotation of the earth drive a complex and variable ocean circulation system. The mechanical energy thus generated, essential for maintaining the dynamics of marine ecosystems, generates turbulent eddies that divide into smaller eddies, and so on until they reach a size (the Kolmogorov scale) at which viscosity overcomes inertia.

Turbulence: characteristics and effects on plankton

The role of turbulent movements at the largest scales (the meso- and macroscale, from metres to hundreds of kilometres) is mainly one of transport. At the smallest scales, of the order of millimetres (small scale and microscale turbulence), the velocity gradients generated by turbulence directly affect particles in the size range of plankton organisms, a community suspended in the water column that includes practically all biological groups, from viruses and bacteria to fish larvae.

The organic matter that fuels the marine food webs is produced by phytoplankton or "plant plankton", which includes unicellular algae of very diverse characteristics (Figure 1). Factors ranging from fisheries production to CO_2 capture by the marine ecosystem are largely dependent on the phytoplankton groups that dominate in the community. The seasonal changes of phytoplankton throughout the annual cycle were explained by Ramón Margalef through a conceptual model. In the graphical representation of the model, known internationally as the *Margalef Mandala*, the different biological forms of phytoplankton (groups that share certain functional characteristics) are located in a plane in which the coordinate axes are the intensity of the turbulence and the concentration of nutrients.

Questions arising from Margalef's Mandala have given birth to a fruitful line of work of the Institut de Ciències del Mar (ICM) on the effects of small-scale turbulence on marine plankton as a whole, and led to the holding of the first international course on the theme: *Lectures on Plankton and Turbulence*, funded by the EU and coordinated by scientists from the ICM, the University of Barcelona and other scientific organizations (Marrasé *et al.* 1997).

As the effects of turbulence cannot be isolated from those caused by other factors in the natural environment, laboratory experimentation is necessary. Tanks or aquariums that contain amounts ranging from litres (microcosms) to cubic metres (mesocosms) of seawater are used to control the intensity of turbulence and the conditions of temperature, nutrients and light, as well as the species or communities of plankton to be studied (Estrada *et al.* 1988).

Turbulence is important for the selection of biological forms of phytoplankton because it increases the absorption of nutrients by cells or keeps them in suspension in the water column. Turbulence also affects the migratory strategy of dinoflagellates and can have a negative effect when it is very high (Berdalet *et al.* 2007). Changes in its intensity also interact with the motility, shape and size of cells and cell colonies and help to maintain a high specific diversity (Figure 1)

For zooplankton, provided with chemical and movement microsensors, turbulence can

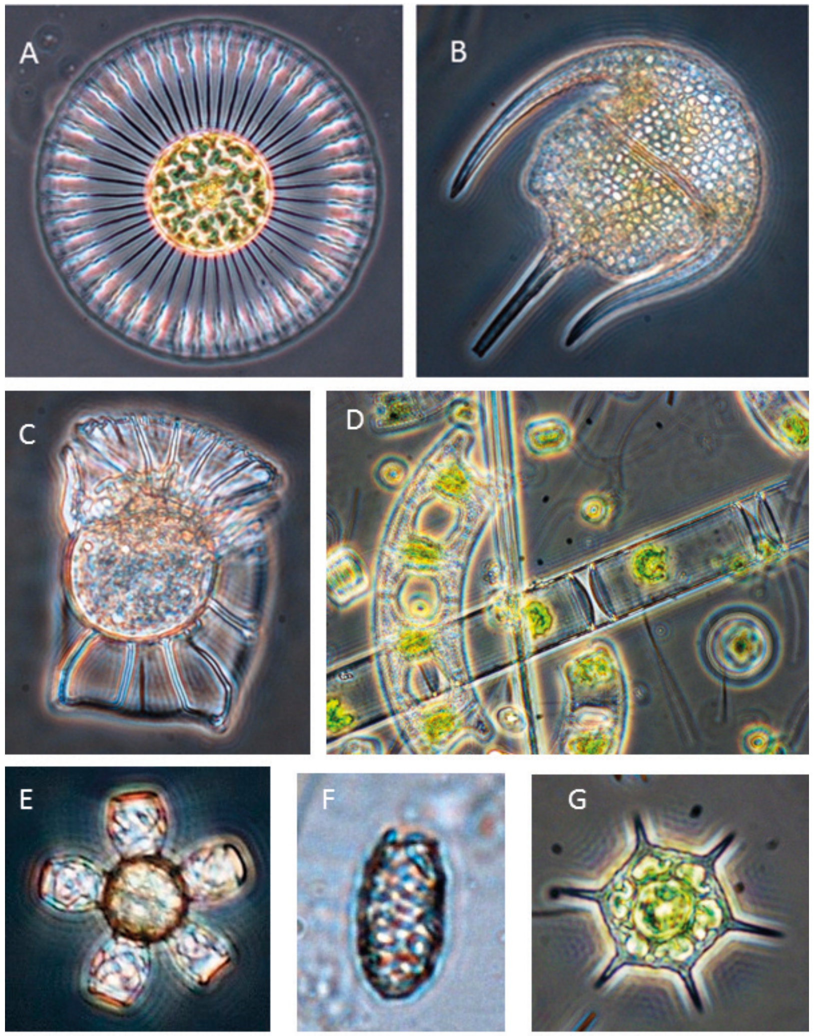

Figure 1. Diversity of forms in phytoplankton (light microscope photographs). A, D, diatoms; B, C, dinoflagellates; E, F, coccolithophores; G, silicoflagellates. The diameter of the cells ranges from little more than about 10 microns in E and F to more than 100 microns in B and C (Photo: M. Estrada).

produce an increase in food intake (greater frequency of contact with food particles), and affect the location of a possible mate by erasing the pheromone track delivered by females as a signal. Water turbulence can also be mistaken with distortions in the water motion generated by prey or predators, inducing attacks or an increase in escape reactions, which have a high metabolic consumption (Figure 2). Other effects of turbulence are changes in the sexual proportion, inducing a greater abundance of males, and the reduction of the average individual size (Saiz 1991).

Turbulence and plankton in a warmer ocean

The climate change that is already underway points to a future ocean that is not only warmer but also exposed to a higher occurrence of turbulence-generating, highly energetic atmospheric events. Temperature and turbulence present analogies (temperature, molecular disorder; turbulence, hydrodynamic disorder), and both trigger very similar responses in some basic properties and activities of organisms.

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Both turbulence and temperature increases induce a higher metabolic activity, an intensification of ingestion rates and a reduction in the average individual size. The latter effect has cumulative consequences on metabolism, since biomass-specific metabolic rates are inversely proportional to size.

While it is known that the vital functions are only possible between a certain range of temperatures that is inversely proportional to the complexity of the organism or function, and that the response of the activity is bell-shaped (it increases with temperature until an optimal value and then decreases), the dynamics of the processes in the case of turbulence is unknown.

Then again, laboratory experiments show that turbulence increases the quotient between the carbon produced by phytoplankton and that breathed by the whole plankton community (Alcaraz *et al.* 2002). Therefore, although part of the consequences of the increase in temperature may be amplified by the similar effects arising from turbulence, the role of the latter in the production/respiration balance introduces a new question. Whatever the case may be, it is clear that turbulence must be taken into account in predictive models of a warmer future ocean.

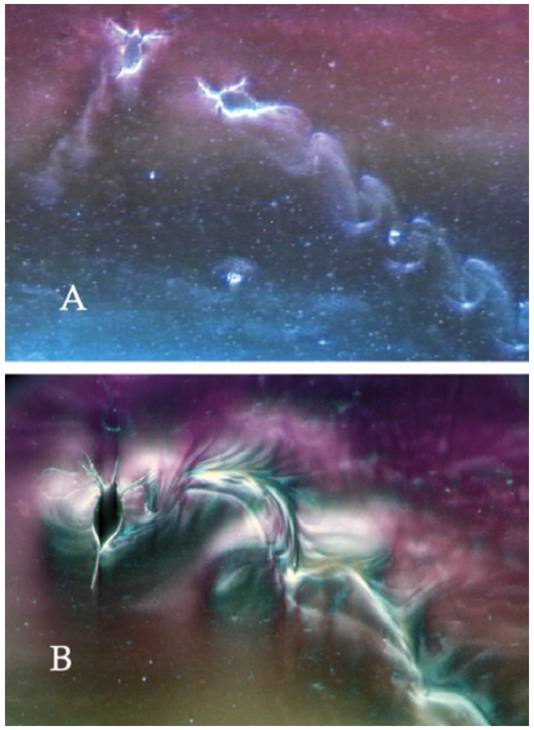

Figure 2. Hydrodynamic tracks created by zooplankton swimming. A, from a carnivorous copepod chasing a prey, by its prey before perceiving the predator's signal and escaping. B, escape reaction of the prey, a freshwater cladoceran (Schlieren optics, Photo: J.R. Strickler).

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From sea up
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Knowing the salt of the oceans
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4.7. Ocean chlorophyll trends in times of global change

Francesc Peters

Chlorophyll is a necessary pigment for photosynthesis, and it serves as a proxy measurement for the biomass of primary producers (mainly phytoplankton) in the ocean. All ecosystems depend totally or partially on the organic carbon produced through photosynthesis, that is, the use of CO_2 and H_2O to synthesize sugars with the energy from solar radiation. In addition, phytoplankton, like terrestrial plants, need inorganic nutrients to grow, and here is where global change comes into the picture.

Concern about the effects of climate change has pervaded society in recent years as scientists now have a high certainty about the human cause of climate change (IPPC 2013). The increase in average global air temperature is without question and is also translating into an increase in surface seawater temperature. The amount of heat per unit volume needed to raise the temperature of seawater is roughly 4500 times larger than that for air and gives an idea of the magnitude of global warming. Surface ocean water masses of tropical, subtropical and temperate regions tend to be relatively depleted of inorganic nutrients, limiting phytoplankton growth, while deeper waters are rich in such nutrients but have no light. Nutrients slowly diffuse upward. One of the consequences of surface seawater warming is that the vertical diffusion of nutrients from bottom waters is further hindered, so phytoplankton growth is expected to decrease.

The Mediterranean Sea is an oligotrophic sea with low inorganic nutrient concentrations naturally occurring in surface waters and low chlorophyll biomass, mainly because of the depth of the basin and the anti-estuarine circulation with respect to the Atlantic Ocean. Oligotrophy increases towards the eastern Mediterranean, which is considered one of the ultraoligotrophic areas of the world. The Mediterranean is also a region where climate change is exacerbated, with a potential to further impoverish surface waters. I hypothesize that this trend should be present in the satellite-derived chlorophyll signal. Thus, in this study I analyse a 20-year time series of satellite-derived chlorophyll in the Mediterranean Sea.

Problem-solving approach using satellite data

I used the surface chlorophyll concentration of the Mediterranean Sea from multi-satellite and Sentinel-3 OLCI observations (Volpe *et al.* 2019). The data were spatially averaged in 179 cells of 1×1 degrees. In order to remove the seasonal (annual cycle) trend in the data, for each cell I adjusted a cubic spline to yearly ensembled data and worked with the residuals from this adjustment. Then, I fitted a linear trend to these residuals. Statistical significance was set at $\alpha=0.05$. Finally, in order to visualize and compare these long-term trends, a Q_{10} parameter, which provides the multiplying factor of chlorophyll after 10 years, was calculated as $Q_{10} = 10^{b*10}$, where b is the slope of the fitted trend. Q_{10} values were averaged over the entire Mediterranean ocean or by subregions. Average values were t-tested (two-tails) against a null hypothesis of $Q_{10}=1$.

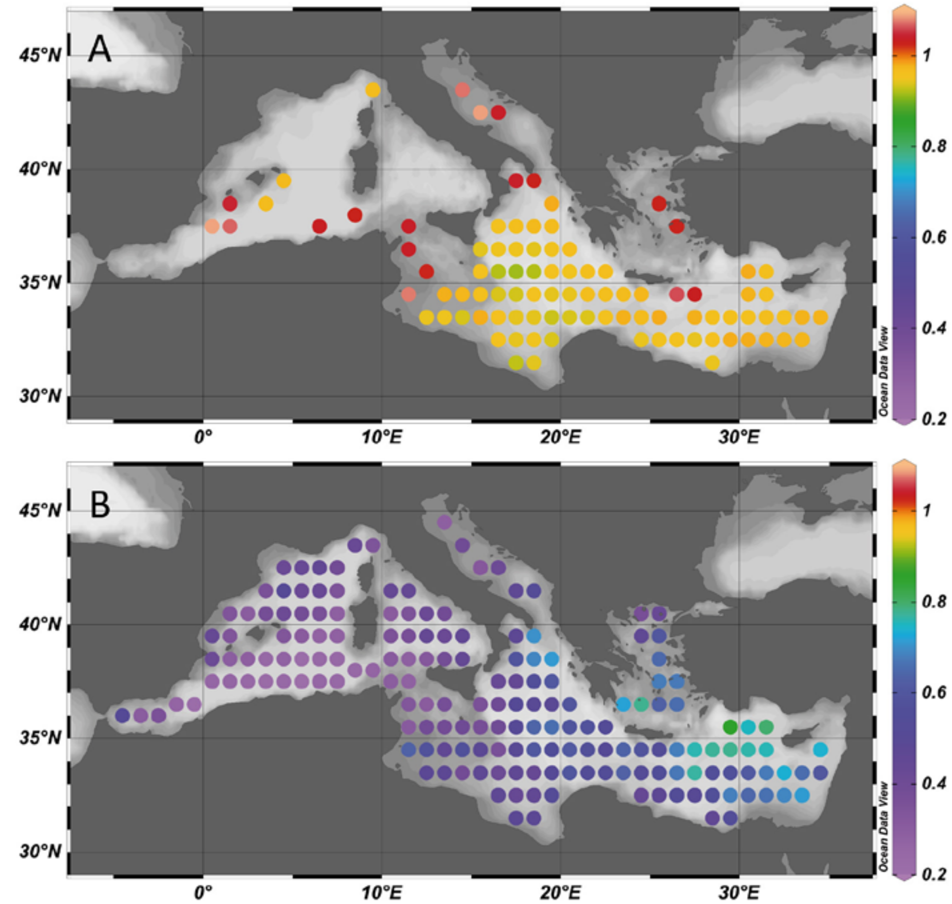

Figure 1. Q_{10} values derived from satellite chlorophyll time series. Only cells with statistically significant trends (p≤0.05) are shown. A, trends for the whole time series (1998 to 2017). B, trends derived from recent years (2013–2017).

Mediterranean chlorophyll trends

From the 1998–2017 times series, there is a slight but statistically significant tendency for chlorophyll to decrease in the Mediterranean, with a Q_{10} of 0.98 (Figure 1A). However, there are regional differences (Table 1). No significant tendency is observed for the western Mediterranean or the Aegean Sea. A tendency for chlorophyll to increase over time is observed in the Adriatic, while decreasing chlorophyll is observed for the Ionian Sea and the eastern Mediterranean (Levantine) Sea. However, the time series of the residuals from the seasonal adjustments do not tend to be monotonically increasing or decreasing. In general, the trends showed increases in chlorophyll over the first half of the series and decreases afterwards. In a second analysis, I focus on the last five years of the series (2013 to 2017). When this is done (Figure 1B), a strong and consistently decreasing trend in chlorophyll is observed with a Mediterranean average Q_{10} of 0.47 (Table 1). The highest decreases are found in the western Mediterranean, in the Adriatic and in the Ionian Sea, while somewhat lower decreases are observed in the Aegean and Levantine seas.

Take-home message

There seems to be a system tipping point between 2007 and 2017, depending on the specific cell considered, for chlorophyll to clearly decrease in the Mediterranean. One could spec-

Table 1. Summary of chlorophyll concentration Q_{10} values (average, se: standard error, and n: number of cells) for the Mediterranean Sea and subregions[†]. T-test significance against a Q_{10} = 1 is p < 0.05 (*), p < 0.01 (**) or p < 0.001 (***).

	Mediterranean	estern Mediterranean	Adriatic	Ionian	Aegean	Levantine
n	179	65	6	49	11	48
Years 1998–2017						
Average (se)	0.985*** (0.003)	1.002 (0.003)	1.041* (0.013)	0.966*** (0.005)	1.004 (0.005)	0.970*** (0.003)
Years 2013–2017						
Average (se)	0.474*** (0.012)	0.336*** (0.010)	0.400*** (0.036)	0.483*** (0.015)	0.601*** (0.039)	0.633*** (0.016)

[†] Western Mediterranean, from the strait of Gibraltar to the strait of Sicily; Adriatic Sea, down to 40°N; Ionian Sea, from 40°N down to Africa and from the strait of Sicily to 20°E; Aegean Sea, from Crete to the north and framed by Greece in the west and Turkey in the east; and Levantine basin, from 20°E to the east, excluding the Aegean Sea.

ulate that the decline in the terrestrial inputs of phosphorus driven by legislation in the northern Mediterranean partly explains the consequent decrease in chlorophyll. However, when such a Mediterranean-wide synoptic trend is observed, a large-scale effect related to nutrient availability is expected more than local or coastal nutrient depletion trends. It seems that this trend fits the hypothesis of a stronger separation of surface and deep water masses owing to increasing water temperatures. Trends in the decrease of ocean chlorophyll have been reported elsewhere (Gregg and Rousseaux 2019), providing confidence for these results. Nevertheless, absolute values of the decrease remain uncertain.

Chlorophyll reflects phytoplankton biomass, and we know that biomass is related to biodiversity (Irigoien *et al.* 2004). For low phytoplankton biomass, there is a direct relationship with species richness, so we should expect a reduction in biomass to be accompanied by a reduction in phytoplankton biodiversity, a worrisome issue if we take into account that the Mediterranean can be considered a hotspot of marine biodiversity (Coll *et al.* 2010). Also, if current high extinction rates observed for land-dwelling organisms are mirrored in the plankton, an additional stress related to biomass could strongly disrupt marine ecosystems. In addition to ecosystem stability issues, there would be important consequences for the fisheries that depend directly or indirectly on phytoplankton biomass. This study also highlights the importance of having long time series when addressing climate change issues. Trends are often small over short periods of time, and longer time series are crucial for proving significance out of the inherent noise.

If the decreasing trends observed for the years 2013–2017 hold and can be extrapolated, chlorophyll levels in the Mediterranean will in ten years be roughly half the current values across the basin, somewhat more in the east and increasingly less towards the west. This will be a drastic change for the entire ecosystem.

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4.8. Phytoplankton and the elements of life

Mariona Segura-Noguera, Elisa Berdalet, José Manuel Fortuño

Living organisms are composed mostly of six elements which are present in the oceans as dissolved gases and nutrient salts: hydrogen (H), carbon (C), nitrogen (N), oxygen (O), phosphorus (P) and sulphur (S). Phytoplankton organisms, both microalgae and cyanobacteria that are being drifted away by marine currents owing to their small size, incorporate these elements and use solar energy to build organic matter to live and reproduce while producing oxygen. The growth of phytoplankton therefore depends on the combination of light availability –restricted to surface waters– and nutrients from the deep waters of the continents or oceans.

These tiny creatures play key roles sustaining our life on Earth, affecting our health, food, and regulating the climate. Phytoplankton constitutes the first step of the marine food webs, and it is a source of food for heterotrophic microorganisms, small crustaceans, fish larvae, and even whales. Especially in areas of nutrient-rich deep-water upwelling, phytoplankton can sustain large fisheries from which human beings are nourished, and that are a source of wealth for many countries. In addition, from the incorporation of CO_2 by phytoplankton through photosynthesis, and subsequent conversion into different forms of biomass in the trophic web, C is transported by sinking to deep areas of the ocean, where it remains for long periods of time. Through this process, known as the “biological pump” of carbon, phytoplankton plays a key role in regulating the climate of our planet. However, when the combination of certain environmental factors favours rapid phytoplankton growth, excess biomass cannot be consumed efficiently, and its degradation results in the deterioration of the overall ecosystem quality (see Berdalet *et al.* 2022).

Redfield stoichiometry: between taxonomy and physiology

In the mid-20th century, the oceanographer Alfred Redfield discovered that in twilight waters of all the oceans there was a constant relationship between nitrate, phosphate, inorganic carbon and dissolved oxygen. Since the concentrations of these compounds increase with depth because of the remineralization of organic matter (mostly plankton) sinking from surface waters, Redfield deduced that the stoichiometry (i.e. the ratio between the corresponding elements) of plankton had to be coincident with the relationship between the same dissolved elements in deep dark waters, which was $-O_2/C/N/P = -138/106/16/1$ (Redfield 1934). However, Redfield noted that these values were an average that could change depending on the taxonomic composition (in species) of the settling organic matter. Actually, it has been proved that the most abundant phytoplankton groups (diatoms, dinoflagellates, and coccolithophores; Figure 1) exhibit varying stoichiometries. Diatoms have a cell wall of amorphous silica, coccolithophores are covered by plates of calcium carbonate (coccoliths), and dinoflagellates have a C-rich cellulose cell wall and a relatively large nucleus. Thus, the concentration of C per unit volume is greater in dinoflagellates and coccolithophores than in diatoms, and dinoflagellates require more P per unit volume than diatoms (Segura-Noguera *et al.* 2016), which have large cytoplasm vacuoles. Plankton stoichiometry is also flexible: when nutrients are abundant, phytoplankton can reproduce, increasing the production of proteins (rich in N) and DNA, RNA and ATP (rich in P), and the C/P and C/N stoichiometry therefore decreases. On the other

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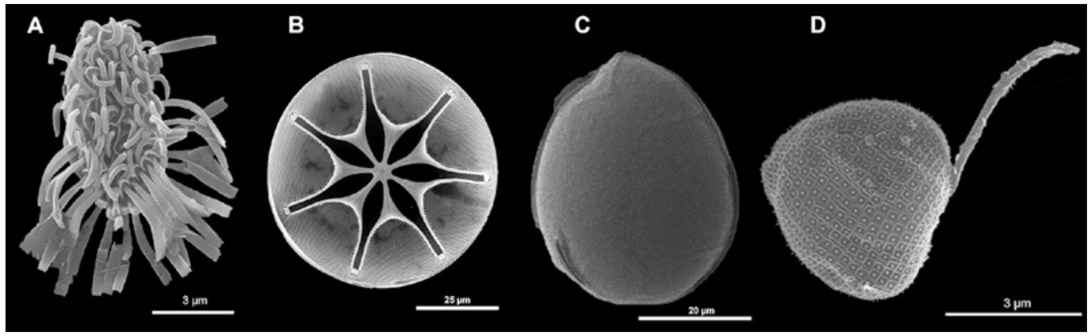

Figure 1. SEM images of representative phytoplankton obtained at the ICM Electron Microscopy Service: A, *Picarola margalefii*, coccolithophore; B, *Asterolampra marylandica*, diatom; C, *Ostreopsis* cf. *ovata*, dinoflagellate; and D, *Pyramimonas* sp., chlorophyte.

hand, when nutrients are scarce, the proportion of C-rich compounds (carbohydrates and lipids) increases, and so do the C/N and C/P ratios.

The Redfield ratio is still today considered a key parameter for characterizing the nutritional state of phytoplankton (and the microbial component in general) and for understanding the flows of the main elements of life in the oceans by combining in situ measurements and models. The classical method for determining the total elemental content of seawater samples, consisting in concentrating seawater in filters, overestimates the quantities of C and N in plankton and does not allow the physiological or nutritional status of microorganisms to be discriminated at the individual level. This has been achieved very recently thanks to technical advancements in the field of electron microscopy.

Phytoplankton taxonomy and stoichiometry in a single instrument

Researchers of the Institut de Ciències del Mar (ICM) have long shown an interest in the study of plankton organisms. The ICM (formerly the Instituto de Investigaciones Pesqueras) acquired its first scanning electron microscope (SEM) in 1975, and since 1987 the ICM's SEMs have been equipped with an X-ray detector and a spectrometer for elemental microanalysis. At the ICM's Electron and Optical Microscopy Service we have the tools to characterize the chemical composition of cells at the individual level with an SEM and its coupled detectors. With the SEM we can obtain high-resolution images (up to 3 nm) and quantify the elemental concentration of phytoplankton using X-ray microanalysis (XRMA). The Electron and Optical Microscopy Service has contributed to many scientific publications, describing for the first time new species of coccolithophores and dinoflagellates, as well as structures of crustaceans, cephalopods and fish.

Recently, at the ICM we have improved a method for studying the elemental composition of phytoplankton using XRMA (Segura-Noguera *et al.* 2012; Figure 2). This technique can be used to quantify stochiometric changes in the cells as a function of nutrients and light availability. Thus, the ICM will contribute to the detailed understanding of the transfer of chemical elements through the trophic webs, including situations of imbalances in harmful blooms of phytoplankton. It will also be able to describe current biogeochemical cycles in different climate change scenarios, in which global warming can lead to changes in the dynamics of stratification and mixing of the water column. These changes, as explained above, modulate the availability of nutrients and light for phytoplankton growth on which marine organisms, and ultimately humanity, depend.

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Marine ecosystem models for understanding and
Reconstructing the climate

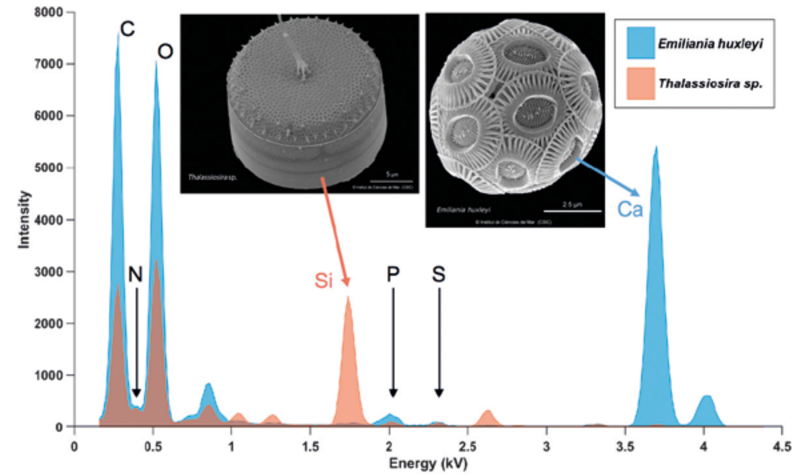

Figure 2. X-ray spectra highlighting peaks of vital and characteristic elements of different phytoplankton groups: calcium (Ca) in the coccolithophore *Emiliania huxleyi* and silicon (Si) in the diatom *Thalassiosira* sp.

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4.9. What role would zooplankton play in a future ocean?

Albert Calbet, Enric Saiz

Good things often come in small packges and, indeed, the smallest organisms are the most numerous and frequently the most important for the functioning of nature. Plankton are mostly invisible to the naked eye but crucial to marine trophic food webs. Plankton organisms are responsible for life on Earth: they provide us with half the oxygen we breathe, and without them we would certainly not eat fish. Conversely, they are also the precursors of fossil fuels such as oil. Nobody is perfect.

The main components of plankton and their functions

In a teaspoon of seawater (about 5 mL), we can find roughly 50 million viruses (don't worry, they're not harmful to humans!), five million bacteria, a few hundred thousand small unicellular flagellates, about five heterotrophic ciliates (Figure 1) or dinoflagellates and –if we are lucky– one small crustacean such as a copepod (Figure 2). The plant part of the plankton is called phytoplankton and the animal part zooplankton. Although the term zooplankton includes both unicellular and multicellular organisms, we typically separate these groups by size into microzooplankton (mostly unicellular; 20–200 µm) and mesozooplankton (multicellular or proper animals; 0.2–20 mm).

Every group of zooplankton has its function in the marine ecosystem (Steinberg and Landry 2017), although we can consider all of them consumers of bacteria, phytoplankton and even other zooplankton. Microzooplankton, for instance, are the major grazers of phytoplankton in the oceans and are therefore a key step in the transfer of matter and energy through the food web (Schmoker *et al.* 2013). Mesozooplankton, mostly little crustaceans such as copepods, are also voracious consumers of phytoplankton and microzooplankton, and they are the main food for fish (and sometimes for whales, although most whales prefer krill). In turn, through their metabolic activity, zooplankton also help release the nutrients accumulated in living matter,

Figure 1. The tintinnid ciliate *Favella* sp., a common member of the microzooplankton (source: Albert Calbet).

Figure 2. *Calanus hyperboreus*, an important high-Arctic copepod whose habitat is threatened by climate change (source: Albert Calbet).

making them available for algae again; this process is called nutrient recycling. Well, yes, we thought we had invented recycling, but it turns out that it has existed for millions and millions of years. In fact, in the sea, almost everything is used and very little is wasted.

Zooplankton in a future ocean

It is now undeniable that the Earth is warming at a faster rate than it should due to merely natural causes. It is important to understand, however, that the climate of the Earth cannot be understood without the ocean and vice versa. It is therefore expected that a higher temperature will have consequences on the stability of the water column, affecting the extent and intensity of the seasonal phytoplankton bloom, which may influence the recruitment of key copepod species in many ecosystems. For instance, a higher degree of stratification and lower inorganic nutrient contents of the ocean surface layers may result in changes in the composition and size (they will be smaller) of their microbial components, resulting in a less efficient and profitable transfer to copepods and therefore negatively affecting copepod production, and fish and fisheries. Warming could also modify the periodicity and intensity of upwelling and have important consequences for the overall productivity of the entire marine ecosystem and major fisheries. Through complex climatic feedbacks, a higher temperature can lead to variations in the direction and intensity of currents and influence the distribution of marine species. For instance, phenomena such as El Niño that control the fisheries of the west coast of South America depend directly on climatic conditions. At a more local scale, jellyfish outbreaks, invasion of new species, the increase in the frequency and amplitude of harmful algal blooms (also related to other anthropogenic impacts) and the expansion of anoxic zones in the seas and oceans are a few examples of the changes that await us in the immediate future.

Not all is lost, though (or perhaps it is)

Throughout evolution, plankton life history traits have been tightly coupled to their environment, making them very sensitive to climate change. However, plankton also have some plasticity and can adapt to changes in temperature, especially if they are gradual. In most cases, observations have shown that planktonic organisms under warmer conditions end up being smaller than they are at lower temperatures. In fact, in the laboratory, it has been shown that, after a period of adaptation to higher temperatures, both phytoplankton and zooplankton end up regulating their metabolic rates and offsetting the effects of temperature. If, for example, we expose algae to five degrees Celsius above the temperature at which they normally live, their respiration rate will exceed their photosynthesis rate. This is because respiration is more sensitive than photosynthesis to thermal changes. However, after many generations in the new temperature conditions, both rates will return to their original balance.

Why should we care? The problem is that, during this adaptation process, which can last for years, the species in question is in metabolic imbalance and is not competitive with other, better-adapted species. A clear example is a displacement of the copepod *Calanus finmarchicus* (which has an affinity for cold water) by *Calanus helgolandicus* (which has an affinity for warmer water) in the North Sea (Edwards *et al.* 2013). The first species is very prolific and nutritious, and thanks to it all the cod fishery in the area is maintained. It seems that *C. helgolandicus* has less lipid reserves than *C. finmarchicus*, so the yield of these important fisheries is changing. We find another example in the biogeographical shifts in zooplankton community composition caused by ocean warming. These displacements of communities seeking the ideal water temperature will certainly affect zooplankton-mediated carbon sequestration and transfer to fish production, though the communities in question will at least have the possibility to migrate. However, what is going to happen in the tropics, where the inhabiting species are already at the limit of their thermal capacities, is still unknown. Will the plankton of these ecosystems survive a temperature rise like the one expected at the end of the century?

It is hard to predict, but many species will certainly be lost on the way.

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4.10. The ocean recycles organic matter and sequesters carbon

Miguel Cabrera-Brufau, Pedro Cermeño, Cèlia Marrasé

Marine phytoplankton are photosynthetic microorganisms that use solar radiation, inorganic carbon and nutrients to produce organic matter (OM) and release molecular oxygen. Phytoplankton photosynthesis produces both particulate organic matter (POM) and dissolved organic matter (DOM), and these two fractions are subject to different biological consumptions and transformations as well as different physical transport processes. Phytoplanktonic POM can be directly ingested by zooplankton (microscopic animals that in turn serve as food for larger organisms), whereas DOM can enter the trophic web through microbes that grow on the dissolved compounds and are then consumed by bacterial grazers. Both fractions can be exported downwards from surface waters: POM can sink on its own or be transported by swimming organisms or downward movements of water masses, while DOM can only be exported

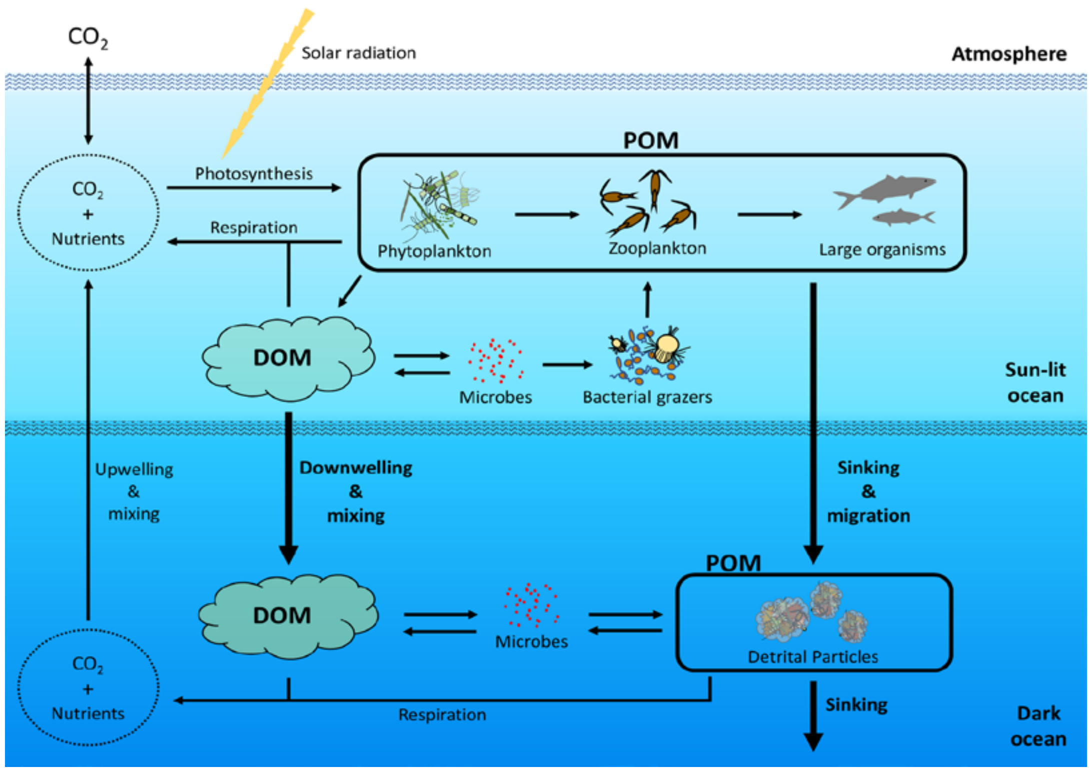

Figure 1. Scheme showing the main OM export processes of the biological carbon pump (BCP). DOM (dissolved organic matter); POM (particulate organic matter).

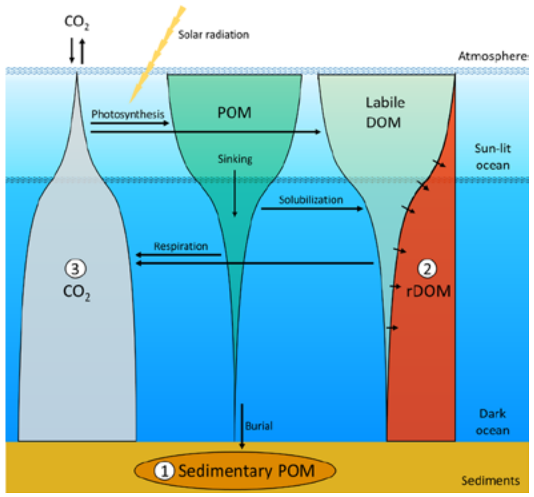

Figure 2. Scheme of the three ocean C-storage forms that depend on the biological carbon pump: Sedimentary POM (1), recalcitrant DOM (2) and deep ocean CO_2 (3).

through physical processes of downwelling and mixing. The processes that transport OM from the surface to deeper waters are collectively referred to as the biological carbon pump (BCP) (Figure 1). As OM is transported downward, it is degraded and respired, releasing nutrients and CO_2. Through the export and processing of OM, the BCP maintains vertical gradients of nutrients, CO_2, DOM and POM that have important consequences for the functioning of marine ecosystems and the modulation of the earth's climate.

Organic matter recycling

Marine phytoplankton primary production is generally limited by sunlight availability and by the concentration of inorganic nutrients (mainly phosphorous and nitrogen). Thus, the dynamics and distribution of inorganic nutrients are of utmost importance for sustaining marine ecosystems which, in turn, influence the distribution of inorganic nutrients through biological activities. This interconnection of nutrients and phytoplankton is largely governed by solar radiation: the sun-lit surface ocean is dominated by photosynthesis, which consumes inorganic nutrients, whereas in the dark ocean the respiration of OM releases nutrients that accumulate until upwelling and vertical mixing bring them back to the surface.

Most OM is degraded and respired within the surface layers of the ocean, recycling nutrients that can support some primary production. This is termed recycled primary production and is well known to be the main process responsible for the supply of nutrients to regions such as tropical gyres, where marked thermal stratification prevents nutrient-rich deep waters from reaching the surface. These systems are relatively unproductive; they predominantly support small-sized phytoplankton through highly efficient microbial food webs unable to sustain important fisheries or transfer OM beyond the sun-lit zone. By contrast, in regions where deep, nutrient-rich waters emerge to the surface, primary production is enhanced, as marine phytoplankton can use not only the locally recycled nutrients but also those accumulated in deep waters through their journey across the dark ocean. This "external" input of nutrients supports what is known as new primary production and enables the ecological selection of large-sized phytoplankton species, which sustain global fisheries and OM export to the deep ocean through the classical trophic chain. Overall, all life in the oceans depends upon the recycling of OM and nutrients, either at the surface (recycled production) or in the deep ocean (new production) (Eppley and Peterson 1979).

Carbon sequestration

The ocean's capacity to sequester C is determined by physical, chemical and biological processes, and C can be stored away from the atmosphere in both inorganic and organic forms. Three main climate relevant C-sequestration mechanisms arise from the downward export of OM by the BCP (Figure 2).

First, the sinking of POM leads to part of it becoming buried in marine sediments. This fraction is estimated to represent less than 1% of the OM produced at the surface every year, but it is one of the main biological mechanisms regulating atmospheric CO_2 at geological timescales (De La Rocha, 2007). A second mechanism of organic C storage is the accumulation of recalcitrant DOM (rDOM) in the deep ocean as a by-product of the degradation of labile DOM by marine microbes. Multiple factors can make rDOM resistant to degradation, ranging from its intrinsic chemical complexity and diversity to the environmental conditions of the deep sea and the identity of the microbial decomposers. The amount of C stored as rDOM is comparable to that of atmospheric CO_2, and it can be sequestered with minimal losses for thousands of years (Hansell 2013). Finally, even if all of the carbon fixed into OM by phytoplankton is respired back to CO_2 in the oceans, the depth at which this happens can have an important impact on the earth's climate. The deeper OM is respired back to CO_2, the longer it will take for this carbon to come into contact with the surface. The vertical gradient of CO_2 limits the exchange of this gas with the atmosphere and leads to the ocean storing much more carbon than it could if no biological processes played a role. If all life in the oceans were to disappear, this gradient would eventually disappear and the excess CO_2 would be released, approximately doubling the atmospheric concentration of this greenhouse gas (Boyd 2015).

These three mechanisms of carbon sequestration all depend, to a greater or lesser extent, on the degradability of the OM produced by phytoplankton. The carbon in resistant OM reaches greater depths, where it can accumulate, either dissolved in deep waters as rDOM and CO_2 or buried in the sediments as POM. Climate change is likely to modify the distributions of phytoplanktonic types from ones whose OM is fairly resistant to degradation to ones whose OM is more easily respired (Cabrera-Brufau *et al.* 2022). These changes will likely reduce the ocean's biological ability to sequester C, which could exacerbate global warming.

Marine phytoplankton shape nutrient distributions and essentially support all marine biological production, including ultimately important resources such as fisheries. Moreover, the consequences of their activities reach all life on our planet, helping to regulate the earth's climate. However, we are far from fully understanding all processes that control OM recycling and its accumulation in the ocean, which will be critical if we are to accurately predict and hopefully mitigate the consequences of climate change.

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4.11. Studying the coastline. Understanding the border

Jordi Camp, Eva Flo, Albert Reñé, Nagore Sampedro, Esther Garcés

The coastline is the part of the land surface that marks the border between land and sea. Like any border, it is more a concept than a place. It has no physical entity and therefore no properties. Its importance lies in events that take place on each side and the mutual interactions that materialize in flows through them. This approach to the coastline as a border is a useful simplification for addressing the problems related to coastal marine waters and their relationship with human activities.

Understanding the border

The sea close to the continent is very different from the rest. It is more heterogeneous, variable and productive (Flo *et al.* 2011), mainly due to the effect of material flows from the mainland (Figure 1). The communities of littoral marine organisms are modelled according to these flows. The entire coastal ecosystem depends on them and evolves over space and time as a function of changes in flows.

Continental flows are now totally influenced by human activities. The process began timidly in the Neolithic, when we overcame the hunter-gatherer stage and began to settle and organize the territory, an activity that has only grown since then. Current land-use maps are the best indicator, not only of the state of the continents, but also of the characteristics that we can expect from coastal marine waters and the organisms that inhabit them (Flo *et al.* 2019, Basterretxea *et al.* 2018).

The coastline was and is important to humanity. *Homo sapiens* was born inland from the African continent, but now we know that at critical moments in its evolution, when all humanity was a few hundred individuals, it needed the coastline to survive as a species. Currently, with about 8,000 million, more than half of humanity lives on the coast, which represents less than 10% of the earth's surface. The littoral sea continues to arouse great interest for society because it is the area that is best known and most used and enjoyed.

Studying the coastline

Natural sciences arise in response to the need to foresee the future in order to survive. To study, it is necessary to understand, and to understand, it is necessary to manage and thus govern the future as much as possible in order to continue as a species. Natural sciences as a tool for land management are based on more than ten thousand years of trial and error. At sea, on the other hand, ecosystem management is barely a hundred years old, and during the first third of the 20th century, marine resources were still considered practically inexhaustible.

The great inertia of the marine system means that responses to pressures are not very apparent in the short term, and they also show a slow recovery. When the ability to generate pressure is very high, as in the case of current human action, and the impacts and returns take a long time, trial and error is useless. Anticipation is needed, which in turn requires a thorough understanding of the physico-chemical and biological mechanisms and processes that govern the functioning of the system. Obtaining this in-depth knowledge is the ultimate reason for the existence of marine research centres.

There is strong social pressure to prioritize the use of natural values over others. This is especially evident at sea, as the connection between conservation and exploitation is less apparent. A large part of the objectives of marine research centres during the 20th century have been linked to solving problems of fishing exploration and management, extraction of minerals from the seabed and marine dynamics related to sailing. Our institute was born as the Instituto de Investigaciones Pesqueras when fishing was an important part of the country's economy. Its name was later changed to the Institut de Ciències del Mar (Institute for Marine Sciences, ICM), but even today management criteria are closely linked to these values, as is shown by the fact that we still talk about ecosystem services, a clean and productive sea and sustainable fishing.

Without giving up all this, we must move further. We need to deepen our understanding of the intimate functioning of the coastal marine ecosystem, taking advantage of the possibilities offered by new technologies, from molecular biology to remote sensing. We must focus on holistic visions such as those that relate the planning and uses of the territory with the continental flows that reach the sea. Only in this way will we have tools for managing the quality of coastal water and governing the state and evolution of the coastal ecosystem. It is necessary to set priorities for the desirable and possible states of coastal biological communities, without forgetting the use values of the coast, for which society still shows a strong demand. But since not everything is possible everywhere and at the same time, spatial planning problems must be tackled with courage. In the separation of activities, it is necessary to go beyond criteria based only on ecosystem services, which are frequently skewed for speculative reasons. More and more conservation criteria based on ethical and heritage values must be introduced.

Figure 1. Southern Coast of Catalonia. In the background, the town of Alcanar. The complex circulation of littoral sediments resuspended in the sea by an incipient wind contrasts with a perfectly controlled and ordered continent. The image illustrates the differences in knowledge and predictability between the two sides of the coastal border (Author: J. Camp).

The ICM participates in this history linked to the use of the sea, but it has always maintained a concern for basic knowledge and a holistic vision. Thanks to this, it was and continues to be a benchmark organization in many fields of marine science. Given that society pays us, this privileged position obliges us to set guidelines for humanity's relationship with the sea in general and especially with its most threatened part: the coastline. Our accredited scientific excellence gives us the moral authority to be heard, and we must dedicate part of our effort to this.

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4.12. Why do we study polar regions?

Clara Cardelús, Vanessa Balagué, Magda Vila

The poles have always had an inherent appeal because they are remote areas with limited access, and arriving there recalls the epic journeys of the first explorers. This feeling of adventure also accompanies many of the current polar research expeditions that have been carried out for years to further scientific knowledge of these areas (Balagué *et al.* 2021).

Exploring the poles

The Institut de Ciències del Mar (ICM) has been closely involved in scientific expeditions to Antarctica, in particular, for many years. Thanks to the drive, efforts and perseverance of people such as Antoni Ballester, Josefina Castellví, Marta Estrada, Joan Rovira and Agustí Julià, who pioneered Spanish Antarctic research at the ICM, the first Spanish Antarctic Base, BAE Juan Carlos I, was set up in 1987 (Castellví 2007, Estrada 2020). Expeditions of ICM research and technical staff began later in the Arctic, but became more frequent in the 2000s, particularly with the incorporation of Spain as a member of the Arctic Council in 2006.

The Arctic and Antarctic oceans, located in the coldest regions of the planet, occupy 10% of the total surface of the ocean but play a crucial role in global climate regulation. In these oceans the formation of deep water takes place, which we could interpret as the beginning of the conveyor belt that distributes heat and nutrients throughout the global ocean and keeps the earth's climate, production and life in the ocean stable. Furthermore, the polar regions are natural laboratories in which the extreme natural conditions and isolated locations make it possible to carry out research on natural phenomena and fundamental processes that would not be feasible in other areas. To give an example, because of their pristine condition and the remoteness of anthropogenic activity, these oceans are especially important for studies of the interaction between the ocean and the atmosphere, which require the purest possible conditions. However, environmental pollution is a global phenomenon that even reaches the poles, where it affects the food webs. The study of these processes gives us information on the ability of some pollutants to persist over time and travel long distances, thus impacting the environment on a global scale.

Polar oceans and global change

The presence of permanent ice and snow in the polar areas is the object of multidisciplinary study. This white cover at the poles increases the albedo effect, reflecting sunlight and maintaining the temperature of the planet. Studying the loss of sea ice as a consequence of global warming is essential in order to understand the still tentative predictions of the effects of a changing climate (Figure 1). The melting of ice sheets and glaciers in the polar regions can have a strong

Figure 1. Icy landscape in the Gerlache Strait, Antarctica. You can see the almost melted sea ice, in contrast to the permanent continental ice of the glacier. Credit: Clara Cardelús.

influence on present weather and future climate and ocean circulation (World Climate Research Programme). Therefore, research on the cryosphere and its dynamics is especially relevant in the current climate emergency context.

The 40% reduction in the thickness of Arctic sea ice over the past four decades and the collapse of the ice shelves in West Antarctica are some of the most dramatic examples of recent changes that have captured the general interest and sparked a variety of reflections in a scenario of global change. Furthermore, it is known that if the seismic activity leads to severe eruptions in polar areas, the deposition of large amounts of volcanic ash on the ice of the glaciers could affect its albedo and further accelerate the melting of ice.

The ice retreat from glaciers would also change the structure of the permafrost and modify the metabolic activity of terrestrial polar microorganisms that are adapted to living in these extreme conditions and, in the long run, facilitate their colonization by other plant and animal organisms. There are many life processes in the polar oceans that are still little known. The contribution of each group of the food web is vital in order to understand how nutrients are recirculated, how the biogeochemical cycles take place, how some organisms participate in the formation of clouds thanks to the gases they exhale, and how biological activity can capture atmospheric CO_2 and end up being transported to the depths. If the planktonic and benthic organisms of the oceans are not able to adapt to the current temperature increase, the ecological balance of these icy ecosystems could be threatened, affecting the entire food web, including even large predators (Figure 2).

Ice is also an element of interest for palaeoclimatology studies, to find out what the climate was like in the past and try to understand and anticipate what it will be like in the future. The extraction of ice cores and the study of the components retained in the air bubbles of the past can help us determine, for example, the relationship between CO_2 and temperature and

Figure 2. Chinstrap penguin colony on Deception Island, South Shetland Islands Archipelago, Antarctica. Credit: Clara Cardelús.

understand what was happening at times when the increase in temperature was less acute than at present.

It is of great importance to understand how the physics, chemistry, geology and biology of the poles work by collecting data on oceanographic expeditions or taking satellite observations. Polar science can benefit living beings that inhabit the poles, including humans, and help protect the planet. It is necessary to raise awareness, particularly in schools, that everything that happens at the poles has global repercussions, and the new generations need to understand that these remote regions are of great importance with regard to current issues such as global warming and climate change.

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4.13. Ocean acidification: trends, effects and what we have left to learn

Carles Pelejero, Blanca Figuerola, Eva Calvo

Since the Industrial Revolution, the burning of fossil fuels has caused the concentration of carbon dioxide (CO_2) in the atmosphere to increase progressively, from about 278 ppm (parts per million by volume) to the current 414 ppm (the average for 2020 at Mauna Loa Observatory, Hawaii). The concentration would be even higher if it were not for the oceans, which currently absorb about a quarter of the CO_2 that humans emit into the atmosphere. In return, however, this absorption is causing changes in the chemistry of seawater. When CO_2 passes from air to water, it is involved in a series of chemical reactions and equilibria that result in an increase in acidity and therefore a decrease in pH.

Trends

It is estimated that the pH of the ocean surface has decreased by about 0.1 units (from 8.2 to 8.1) since pre-industrial times, and future projections indicate that by the end of the 21st century, depending on anthropogenic CO_2 emissions, the pH will continue to decrease by about 0.3 to 0.4 units more (Figure 1).

For certain locations in the open sea, we have time series in which instrumental pH measurements taken for several decades corroborate the progressive acidification (Bates *et al.* 2014). In coastal areas, the sum of processes (e.g. respiration, dissolution, primary production, calcification, vertical mixing and eutrophication) makes the variability in pH greater and more rapid than in the open sea, and longer series are often needed to detect its progressive decrease.

Effects

Calcifying organisms are, *a priori*, the ones most obviously affected by acidification. As the pH decreases, so does the concentration of carbonate ions, which is a critical parameter for these organisms to build their calcium carbonate structures (coral skeletons and mollusc shells).

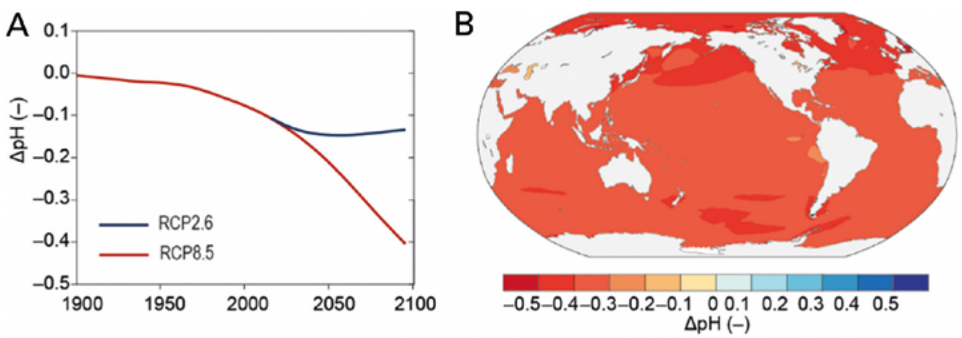

Figure 1. A, simulation of past and future changes in the global surface pH of the oceans, according to optimistic (RCP2.6) and pessimistic (RCP8.5) scenarios (representative concentration pathways). B, changes in the surface pH of the oceans by the end of the 21st century in comparison with the 1850–1900 period according to a pessimistic scenario (RCP8.5). IPCC figure (2019, page 470).

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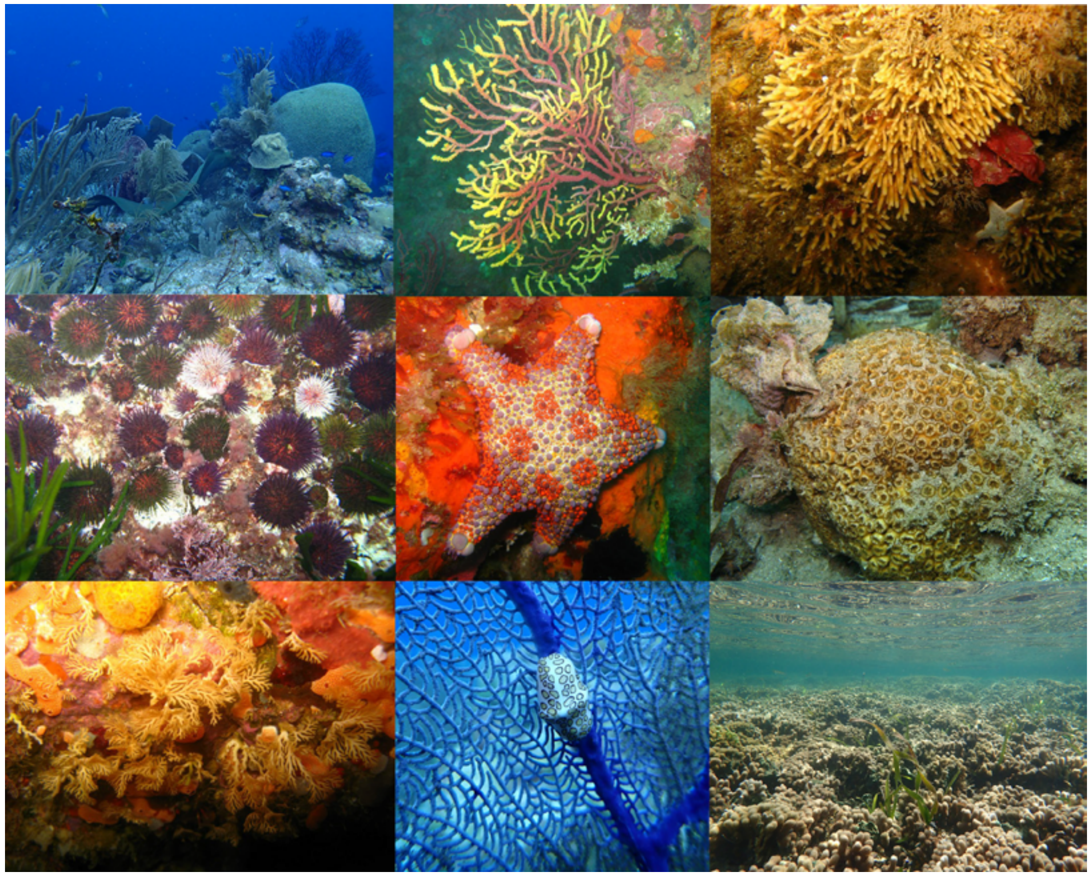

Figure 2. Calcifying organisms with different mineralogies. From left to right and from top to bottom: coral reef from the Belize Barrier Reef; red gorgonians (*Paramuricea clavata*) from the Medes Islands; branched colonies of the bryozoan *Cellaria malvinensis* from the Falkland Islands; sea urchins (*Paracentrotus lividus*) with different colouration (Cantabrian Sea); starfish *Asterodiscides truncatus* from the Poor Knights Islands, New Zealand; a hemispherical coral colony of Mediterranean Madrepora (*Cladocora caespitosa*); bryozoan colonies of the genus Hornera of the Falkland Islands; a flamingo tongue snail *Cyphoma gibbosum* feeding on a gorgonian in the Coral Reef of Belize; and a coral reef formed by species of the genus *Porites* (Bocas del Toro, Panama). Photos by Blanca Figuerola.

In addition, the vulnerability of these structures to dissolution depends on their mineralogy. Calcifying organisms generally deposit two mineral forms: calcite, as in the case of foraminifera (protozoa) and coccolithophores (unicellular algae); and aragonite, as in the case of corals and pteropods (pelagic molluscs), which is generally more soluble in water than calcite. Some species may also incorporate significant amounts of magnesium (Mg) into the calcite, as is the case with many echinoderms and bryozoans. High-Mg calcite can be even more soluble than aragonite. Furthermore, the Mg content in these skeletons generally increases with temperature. Therefore, in these organisms, warming and acidification of the oceans are expected to increase the vulnerability of their skeletons to dissolution.

Calcifying organisms play key roles in ecosystems and in the carbon cycle because some are essential food for animals at higher trophic levels, some (e.g. corals and bryozoans) form unique habitats for many species, including commercial ones, and some (e.g. foraminifers and coccolithophores) act as a carbon reservoir because their skeletons or shells accumulate and are preserved in seabed sediments when the organisms die (Figure 2). In addition to the effects on calcifiers, progressive acidification can also accelerate the production of toxic algae and alter the physiology and nutritional values of species (e.g. reduce the omega-3 fatty acids), with negative consequences for the rest of the food web.

Recently, the links between the state of the oceans and human health are also being highlighted, and ocean acidification is one of the issues involved (Falkenberg *et al.* 2020). This paper suggests that this phenomenon could have an impact on human health and well-being, for example through alterations in the quantity and quality of marine food resources or the disruption of natural environments of high interest for recreational activities (e.g. coral reefs). In addition, acidification could have consequences in very different areas: very recently, for example, a study suggested that a decrease in pH could be accompanied by an increase in the intensity of lightning discharges over the oceans (Asfur *et al.* 2020).

What we have left to learn

Research on the problematics of ocean acidification experienced a major boost in the 2000s, which continues today. Initially, much of the research focused on calcifying organisms, especially tropical corals, which constitute one of the richest ecosystems on Earth and are one of the most affected by this phenomenon. Subsequently, the range of organisms studied was expanded, and all indications are that this process will lead to losers and winners, causing gradual changes from some species to others. More recently, possible synergies between acidification and other global changes, such as warming, have also started to be considered, incorporating the fact that marine organisms are subject to multiple rather than individual stressors.

Future research should focus primarily on 1) strengthening instrumental monitoring programmes throughout the water column to delimit the variability and trends in progressive acidification, 2) experimenting with marine organisms, combining different stresses in addition to acidification, such as warming, deoxygenation, changes in salinity and nutrients, 3) furthering the study of impacts according to different mineralogies of calcifiers, 4) experimenting with and studying naturally acidified environments (e.g. in areas with CO_2 emissions of volcanic origin), 5) determining environments that could serve as refuges because of their role as regulators of acidity (e.g. marine phanerogamous forests), and 6) contextualizing present changes through the reconstruction of past pH levels, for example through the analysis of boron isotopes in fossil calcium carbonate fossils (Pelejero *et al.* 2010).

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4.14. Utility and challenges of marine ecosystem models for a better understanding and management of the ocean

Marta Coll, Jeroen G. Steenbeek

The world's oceans are experiencing rapid ecological and socioeconomic changes caused by global environmental change, and human activities that affect marine resources are heterogeneously distributed and overlap spatially. Historically, the exploitation of marine resources has been a primary driver of change, followed by pollution, mechanical habitat destruction and, more recently, species introduction and human climate change. Environmental change impacts on biophysical and ecological properties of the ocean and affects its biological organization at multiple levels, including genes, species, populations, communities, ecological interactions and geographic distribution of marine species.

A transformation to sustainability is key to adapt our socioecological systems to changing environments. However, scientific understanding about how the oceans will continue to change into the future is limited. This includes deepening our understanding on how marine ecosystems function and how climate change will alter them, with potential synergies with other socioecological drivers of change. This knowledge is essential for managing human activities in an informed and proactive way, mitigating and adapting to climate changes and improving ecosystem and societal resilience.

In response, there is a strong push for the ecosystem-based fisheries management (EBFM) approach (Christensen and Maclean 2011), and more generally for the ecosystem-based management (EBM) approach, which include the establishment of management initiatives that consider changes in human activities, the ecosystem and the environment and factor their interactions and feedbacks (Dolan *et al.* 2016) (Figure 1).

Marine ecosystem models as emergent integration tools

To predict the future of the marine ecosystem and its services, we need to adopt an integrated view of the ocean as a socioecological system that encompasses the dynamics of living and non-living components (both commercial and non-commercial) and the effects of anthropogenic activities and climate variability and change. Powerful modelling techniques can integrate this view into holistic frameworks to better understand the cumulative effects of human activities within a dynamic spatio-temporal context (Steenbeek *et al.* 2021).

The last few decades have witnessed extensive development of modelling techniques in both the terrestrial and the marine domains. Rapid development of atmospheric-ocean circulation models, including biogeochemical processes in earth system models (ESM), has improved the scientific capability to project the climate system, which in turn has helped inform the UN Intergovernmental Panel on Climate Change (IPCC).

Separately, ecosystem models have been developed to investigate the functioning of ecosystems beyond primary producers. These models are conceptual and theoretical frameworks that represent a synthesized understanding of all major parts of an ecosystem and can integrate large amounts of knowledge about ecosystems representing different levels of biodiversity, processes and drivers (Fulton 2010). Over the last three decades, there has been a great increase in such modelling frameworks, especially in the marine realm with the development of marine ecosystem models (MEMs) (Figure 2). MEMs include several approaches and have been applied to analyse past and future dynamics of marine ecosystems and to test interactions of multiple drivers and alternative management strategies. They are being used to project changes in marine ecosystems at a local, regional and global scale around the globe.

Regional MEMs are primarily deployed to integrate biological and ecological knowledge from local studies in order to obtain relevant information about the functioning and structure of marine ecosystem types, the ecological role of key species and the effect of interactions from multiple drivers. They are also used to explore trade-offs and effects of alternative management options, contributing to EBFM and EBM (Figure 1) (Christensen and Maclean 2011).

At the other side of the spectrum, global MEMs couple environmental, ecological and socio-economic data to assess how cascading impacts of ecological disturbances affect species movements, fishing fleet mobility and availability of ecosystem services across vast distances through ocean currents. Global MEMs contribute to the urgent need to understand global changes within the context of the IPCC and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). They are synthesized into ensemble model projections, helping to extend the scientific capability to project what the future oceans may look like, to determine how different scenarios may play out and to quantify uncertainty in model projections (Lotze *et al.* 2019).

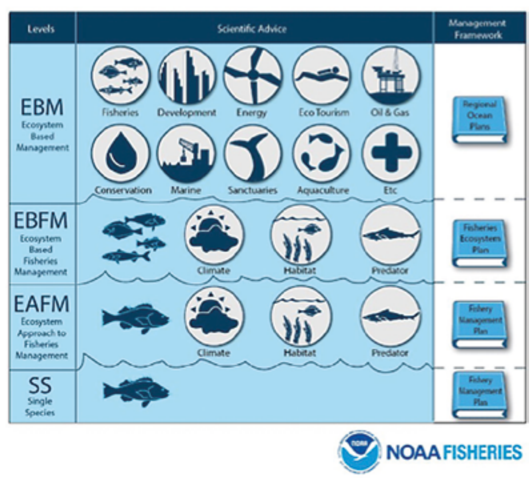

Figure 1. Schematic representation of science advice needed to transition from single stock to ecosystem-based management approaches (after Dolan *et al.* 2016).

Major challenges ahead

Despite the unprecedented development of ESMs and MEMs and the capabilities for projecting the climate system, the available models have limitations that ultimately affect their ability to inform management and policy processes (Heymans *et al.* 2020). For example, only a few MEMs are able to consider direct and indirect ecological dynamics from primary producers to predators, capturing the multilevel impacts of global change on a diversity of spatial-temporal processes. MEMs are limited in their ability to predict the capacity of species to invade new ecosystems. Most current state-of-the-art models are limited in their ability to consider how eco-evolutionary dynamics may interact to condition and modify species traits, patterns and interactions, and in their capabilities to interlink land-ocean interactions.

Therefore, MEMs face great challenges ahead to contribute to a better understanding and management of the oceans (Steenbeek *et al.* 2021). There is an urgent need to extend their ability to project ocean biodiversity, associated ecosystem services and use patterns, and how these tightly interconnected social-ecological systems will change. Priorities for development include linkages with near–real-time observational data, interoperability with emergent modelling platforms that address socio-economics, improving the ability to execute comprehensive uncertainty analyses and model validations, engaging stakeholders

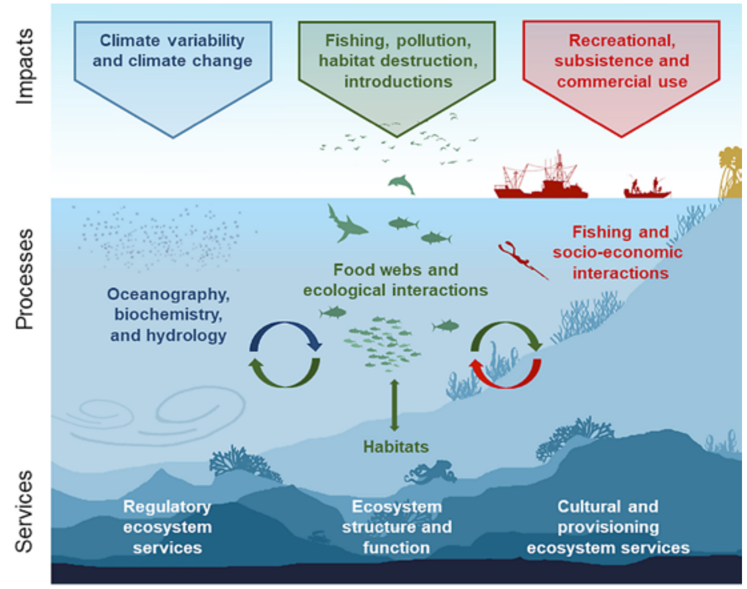

Figure 2. Marine ecosystem models are powerful tools for integrating knowledge about environmental and ecosystem dynamics, human-induced climate change and other activities, and for resource management (source: the authors).

in participatory modelling to capture local ecological knowledge, and the ability to extract emergent properties of socioecological systems. Importantly, the uneven distribution of research capabilities and data availability between regions and countries makes it urgent to work on capacity building, as regions with fewer resources tend to be located in hotspot areas of biodiversity and are faced with deficiencies in monitoring and management enforcement (Heymans *et al.* 2020).

The UN Decade of Ocean Science for Sustainable Development and the Decade on Ecosystem Restoration provide the ocean science community with a unique opportunity to address these big challenges. Major advances in MEM capabilities can contribute substantially to the Convention of Biological Diversity and its post-2020 global biodiversity framework, and can inform the IPCC, the IPBES and the Sustainable Development Goals, in particular SDG14 on the conservation and sustainable use of the ocean, seas and marine resources.

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Opening
Clean ocean
Healthy and resilient ocean
Productive ocean
Predictable ocean
Safe ocean
Accessible ocean
Inspiring and engaging ocean
Indexes

4.15. Reconstructing the climate of the past to understand the climate of today and tomorrow

Eva Calvo, Carles Pelejero

The long-term monitoring of the atmosphere, the oceans and the earth system, especially through data collected by meteorological stations, oceanographic buoys and satellites, has allowed us to identify the rapid changes that the climate system has been undergoing in recent decades. The increase in the temperature of the planet, the decrease in the size of the polar ice caps, the reduction in the extent of sea ice and the rising sea level are some of the consequences arising from the increase in the concentration of atmospheric carbon dioxide (CO_2) caused by human activity. Since many of the processes that control these parameters act on longer time scales than those covered by instrumental records, the only way to have a comprehensive view of the impact that these changes may have on the earth system is through palaeoclimatic and palaeoceanographic reconstructions.

Evolution of the climate and oceans in the past

Palaeoceanography, through the study of marine sediments, allows us to identify past environmental changes (on scales of hundreds to millions of years), their magnitude, direction and speed, and the processes that caused them. (Thomas 2019) (Figure 1).

This information should allow us to know the ranges of the planet's natural variability at different time scales, as well as the sensitivity of the climate system to a given forcing, such as the increase in the greenhouse gases concentration. With studies of this kind, we now know, for example, that the earth experienced much higher temperatures during the Cretaceous, when polar caps did not exist as we know them today, and that climate change can take place abruptly, in a matter of decades. Such rapid changes occurred during the last ice age as a result of changes in global ocean circulation. Another finding has been the close link between climate and the concentration of greenhouse gases (Figure 2), which has also highlighted the unprecedented rate and magnitude of the current increase in atmospheric CO_2.

However, palaeoceanography is a relatively recent discipline. It was not until the 1950s

Figure 1. Coring systems of deep-sea sediments: gravity corer (left and top right) and multicorer (bottom right). Images: Unitat de Tecnologia Marina (UTM-CSIC).

From sea up
Marine sedimentary processes
Mapping the seafloor
Knowing the salt of the oceans
Microbial observatories
Turbulence and plankton dynamics
Ocean chlorophyll trends
Phytoplankton and life
Zooplankton in a future ocean
The ocean recycles
Studying the coastline. Understanding the border
Study of polar regions
Ocean acidification
Marine ecosystem models for understanding and
Reconstructing the climate

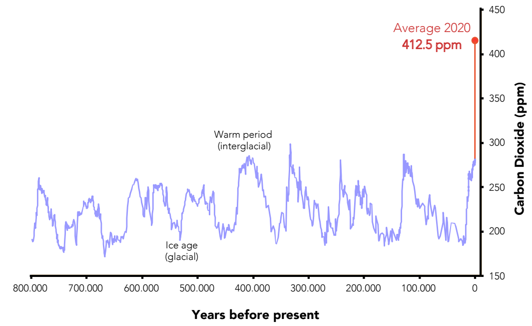

Figure 2. Evolution of atmospheric CO_2 over the last 800,000 years, obtained from the analysis of air bubbles trapped in Antarctic ice cores. In red, the current increase in the greenhouse gas concentration. Adapted from NOAA Climate.gov.

that Cesare Emiliani analysed the isotopic composition of oxygen in fossil foraminifera from sediments from the Atlantic and Pacific oceans and verified for the first time the alternation between glacial (globally cold) and interglacial (globally warm) periods (Emiliani 1955). And it was not until 1976 that these changes in temperature and ice volume, the glacial/interglacial cycles, recorded in the shells of foraminifera, were shown to present the same periodicities as changes in the geometry of the Earth's orbit, demonstrating that they were caused by changes in the solar radiation reaching the earth (Hays *et al.* 1976). Since then, the amount of information that has been extracted from sediments through the analysis of indirect indicators (proxies) is enormous (Chase *et al.* 2018) either 1) through the ratio of chemical elements and their isotopes from the shells of microfossils, which give information on changes in ocean circulation, biological productivity and sea level, or 2) through organic molecules such as alkenones, compounds synthesized by haptophytes, which allow us to reconstruct the temperature of the water where these algae lived (Eglinton and Eglinton 2008). In recent years, technological development and a better analytical capacity have led to the appearance of new proxies that provide information on other parameters, such as pH and seawater oxygenation, which are of great interest in the current context of global change.

And the future?

In the coming years, along with the search for new proxies, there are still many pending questions regarding the functioning of the climate system and the interactions between its components. For example, we do not know the exact causes of the sustained cooling experienced during the Cenozoic, the current geological era, which gave way to the periodic glacial/interglacial cycles of the Quaternary and the Pliocene, although they may include tectonic changes that changed ocean circulation, as well as a progressive decrease in atmospheric CO_2. Nor do we know why the amplitude and periodicity of these glacial/interglacial cycles, modulated by the Earth's orbital configuration, changed about a million years ago. And with regard to the carbon cycle, one of the central questions in the study of the climate and oceans of the past is the low concentrations of atmospheric CO_2 recorded during the ice ages over the last million years. After four decades since the first finding that atmospheric CO_2 oscillated with glacial/interglacial changes, we still do not have a satisfactory explanation for the combination of mechanisms that caused the consistently lower values (around 30 %) of this greenhouse gas during ice ages. In fact, our ability to explain the CO_2-climate relationship, including feedbacks, and therefore the climate's sensitivity to this forcing, is one of the main limitations to predicting the rate and magnitude of potential climate changes in the coming decades.

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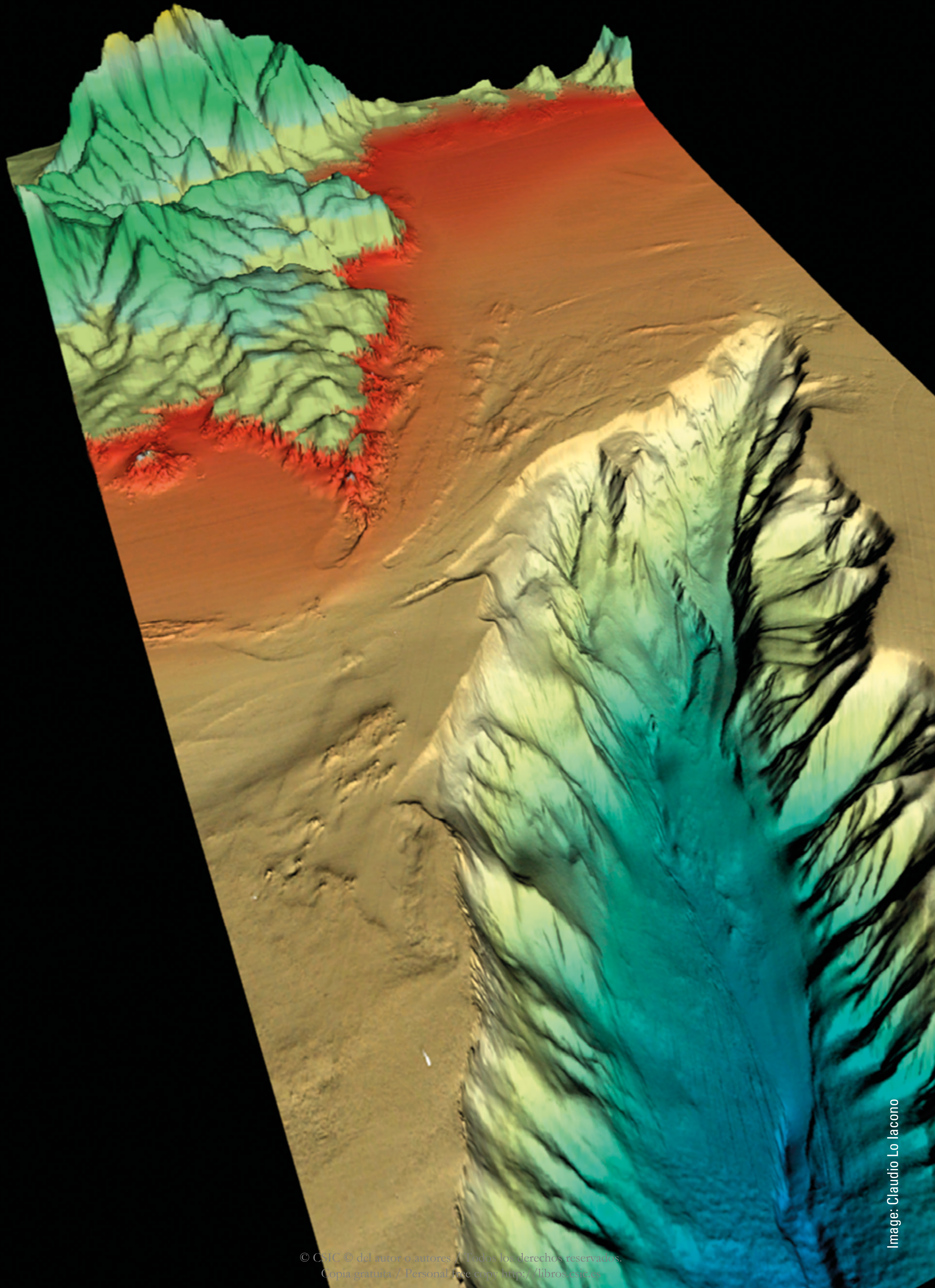

Image: Claudio Lo Iacono

5. Safe ocean

Rafael Bartolomé, Gonzalo Simarro, Marco Talone

According to the World Wildlife Fund for Nature (United Nations, 2015), 50% of the world's population lives within 100 km of the coast, 16 of the world's 23 megacities face the oceans and one billion people live in communities with direct links to the sea.

The need for a safe ocean, i.e. the need to reduce marine risks and losses, is key to the future of our planet's inhabitants. According to the Hyogo Framework for Action of the United Nations Office for Disaster Risk Reduction (UNDRR), a risk is defined as a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation. Risks range from natural hazards (geological, climatic or biological) to those induced by human activity (accidents and environmental changes).

Therefore, the study of geological, biological and oceanographic processes, as well as their associated risks and their proper management, is key to humanity, and marine sciences as a whole is the appropriate discipline for addressing them. In this field of study, ocean observations ranging from the surface to the seabed through the water layer are vital to establish the current state and its variability, to discover the past and to predict the future evolution. Improving observations to advance our understanding of risks aligns with the priorities of the United Nations Decade of Marine Science for Sustainable Development (2021–2030). This initiative aims to mitigate the impact of natural hazards and create a safer ocean so that human communities and infrastructure are better protected from ocean hazards, and to ensure the safety of offshore and coastal operations. The use of appropriate research equipment and international cooperation are two crucial elements of ocean observation, and this is reflected in the contributions in this chapter.

This chapter includes essays on geomorphological structures associated with geohazards (Ercilla *et al.*), including submarine landslides (Urgeles). These underwater structures and phenomena generate offshore earthquakes and tsunamis, and our current knowledge and the future scientific challenges posed by these events are also addressed (Sallarès). The contribution of science and the key role it plays in the management of natural disasters, including biological disasters and the proliferation of marine organisms (Marambio *et al.*), as well as geological, oceanographic (Portabella *et al.*) and human-induced disasters, are also discussed.

5.1. Unveiling hazardous offshore geomorphological features

Gemma Ercilla, David Casas, Ferran Estrada, Belén Alonso

The ocean seafloor is often considered the final frontier today, because though it covers 72% of the earth's surface, it still remains a great unknown. It is an entire world hidden from our eyes that occasionally, convulsively, wakes us up to remind us that there are many active hazardous geological processes occurring today on the seafloor. These processes can impact on people living in coastal areas (about 40% of world's population) or on an entire country, damaging inland and offshore infrastructures and triggering worldwide economic and environmental crises.

Research approach

Multiscale observations and multidisciplinary studies are key for mapping these hazardous offshore features and unveiling their activity. Multiscale observations involve a technological challenge of carrying out multiple complex scenarios on board during the oceanographic cruises, using multibeam echosounders, geophysical systems, long sediment core samplers, autonomous underwater vehicles, remotely operated underwater vehicles, *in situ* testing log instruments, and conductivity-temperature-depth instruments (CTDs). The multidisciplinary approach allows us to bring together the disciplines of marine geology, geotechnical engineering, geophysics, physics oceanography and mathematics. This approach provides multi-criteria diagnoses for understanding the hazardous processes, their triggering factors and event recurrence.

Main offshore geohazard features

The geomorphological studies carried out in the oceans and seas unveil that hazardous processes can occur in any marine domain or environment, from shallow to deep-sea areas. Based on their genesis, four main categories of features are established:

Hazards related to tectonic features. These mostly comprise seismic faults that cause earthquakes. The geomorphological maps indicate that most active faults are located in areas of tectonic boundary plates, where tectonic forces exceed the strength of the rocks (Estrada *et al.* 2018) (Figure 1A, B). The sudden slip of the faulted blocks can produce intensive seismic shaking; the most catastrophic of these events are thrust faults in the subduction zones and transtensional and transpressional strike-slip faults. The last type is common in the western Mediterranean, where detailed geomorphological analysis is essential to improve the accurate analysis of their geometry and dynamics and match it with seismological observations. This approach is leading us to discover unknown seismic fault zones triggering earthquakes today.

Hazards related to sedimentary features. The most common of these are sedimentary slope instabilities. Sediments on seafloor slopes may become unstable and fail, moving significant volumes of sediments downslope over long distances. Their geomorphological analysis unveils three main groups of gravity-driven processes: failures of a coherent mass, which involve slides, slumps and spreads; mass flows, which involve debris flows, mud flows, and debris/rock avalanches; and turbidity currents (Shanmugam and Wang

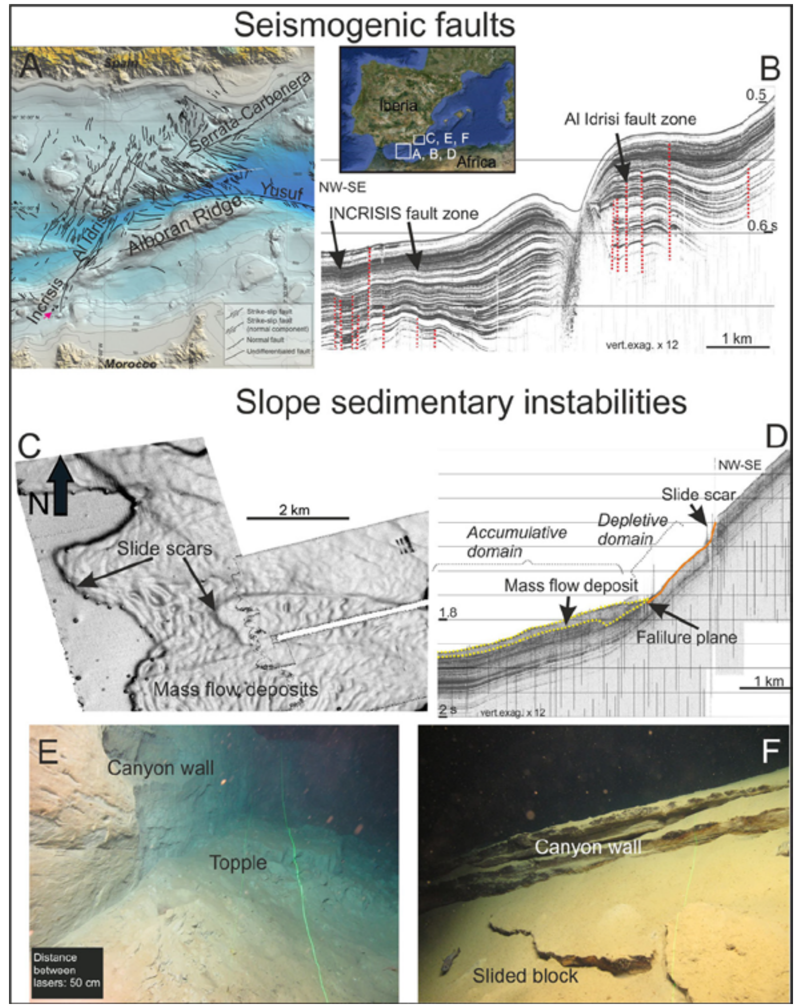

Figure 1. Offshore hazardous features. Seismogenic faults (A, B) and slope sedimentary instabilities (D, D, E, F).

2015) (Figure 1C–F). Geomorphological analysis also unveils the architectural elements of the sedimentary instability deposits, such as failure scars (headwall and sidewall), failure planes, and depletive/extensional and accumulative/compressional domains (Casas *et al.* 2013) (Figure 1C, D). By combining the study of the 2D, 3D and 4D geomorphology of these instability deposits with seismic geomorphology and sedimentology, it is possible to obtain accurate information for assessing the pre- and post-failure situation, establishing their occurrence frequency, and defining the causative factors.

Hazards related to volcanoes. Submarine volcanoes, mainly if they are in shallow waters, and volcanic islands can also represent an offshore hazard. The geomorphic features mapped on submarine volcano flanks indicate that volcanic processes are also associated with active seismic faults and with the collapse of volcanic edifices or part of their flanks, triggering slope instabilities that involve huge volumes of material and blocks (Ercilla *et al.* 2021) (Figure 2E).

Hazards related to fluid-dynamic features. Gas seepage, sudden fluid release (blowout), hydraulic activity, overpressurization, fluidization and breakdown of gas hydrate are some of the hazardous fluid-dynamic processes affecting the seafloor. Their related geomorphic features indicate that these processes lead to the deformation, piercing, faulting, folding, uplifting and subsidence of the seafloor, forming active mud and

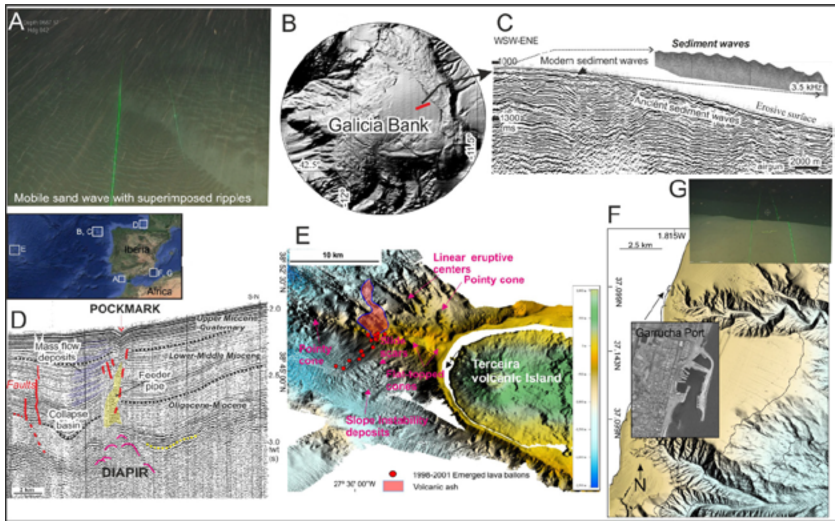

Figure 2. Offshore hazardous features. Bottom current (A, B, C), fluid-dynamic (D) and volcanism (E) features. The Alias-Almanzora-Garrucha canyonhead close to the coast is also displayed; its erosion is affecting the harbour (F).

salt diapirs, mud volcanoes, pockmark fields and scoured seafloors (Figure 2D). In addition, the presence of gas bubbles within the nearsurface deposits is a warning that a reduction in sediment shear strength may occur and trigger slope sedimentary instabilities (Ercilla *et al.* 2021).

Hazards related to bottom current features. Contourite drifts and erosive features such as contourite moats, furrows, channels and terraces reveal the persistent action of the bottom currents acting on the seabed, which commonly reach high velocities on complex and rugged seafloors dotted by seamounts, structural corridors, confined basins, ridges, valleys and diapirs, gateways and seaways. Their action can cause the erosion and scouring of the seafloor, zones with high sedimentation rates and the presence of field areas with mobile bedforms (Ercilla *et al.* 2016) (Figure 2A–C and G).

The hazardous activity of the above features may result in other important secondary catastrophic events, tsunamis, which are mostly triggered by earthquakes, slope instabilities and volcanic eruptions. The cartography of the seafloor also unveils areas with the co-existence of hazardous features, indicating that a cascade effect that involves a chain of events may occur and increase their potential risk, especially in contexts such as tectonic plate indentations, volcanic islands and canyon heads close to the coast (Ercilla *et al.* 2021) (Figure 2F). In addition, these scenarios are commonly affected by hazardous features crossing sea and land, so we need to collaborate with our geologist and geophysicist counterparts working inland for an accurate geohazard assessment.

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5.2. Submarine landslides: the seafloor in motion

Roger Urgeles

On 18 November 1929, a magnitude 7.2 earthquake occurred south of Newfoundland, causing widespread failure of the seafloor. The underwater landslide involved more than 150 km^3 of sediment (approximately 100 times the annual container traffic of Shanghai's port, the world's largest) and evolved into a turbidity current that travelled over the seafloor for about 16 h, breaking several submarine cables along its path (Heezen and Ewing 1952). The cables broke almost instantaneously near the epicentre and at increasing times downslope, accidentally providing the first record of the dynamic history of a submarine landslide. Average peak velocities between cable breaks exceeded 20 m/s (72 km/h). Such a large volume of sediment rapidly accelerating underwater created a tsunami that was recorded across the Atlantic, with tsunami waves of up to 7.5 m in Newfoundland, where property damage was severe and 28 fatalities occurred (Government of Canada n.d.).

The historical and sedimentary record

The 1929 event off Newfoundland is a reminder that not only earthquakes can cause tsunamis. In fact, about 15% of all tsunamis are caused by submarine landslides or landslides entering a body of water. One only needs to pull out the newspaper archive to recall landslide-triggered tsunamis such as those of Nice, France in 1979; Sissano, Papua New Guinea in 1998; Stromboli, Italy in 2003; Haiti in 2010; and Palu and Anak Krakatau, Indonesia in 2018. The existence of significantly larger events in the late Quaternary record is a warning of the hazard and risk posed by such events. Large submarine landslides have been mapped in all oceans and marine sedimentary settings, although their distribution and frequency varies significantly between those settings. Tectonically active margins appear to have a high frequency of events, although their magnitude (size in terms of area or volume) is not as large as that of submarine landslides in passive margins (Urgeles and Camerlenghi 2013). Submarine landslides on low and mid-latitude continental margins appear to occur randomly in time, but those of high-latitude continental margins, where the sediment dynamics is strongly constrained by glaciation-deglaciation cycles on the continental shelf, appear to cluster during deglaciation (Llopart *et al.* 2015).

Causes of submarine landslides

Submarine landslides can occur for many reasons, but generally a distinction is made between those that are inherent or affect the stability of the slope in the long term, usually identified as pre-conditioning factors controlled by climatic and environmental changes, and those depending on external processes or triggering mechanisms setting off the failure. Pre-conditioning factors involve processes that typically take place over long periods of time. These include deposition of sediments at a pace that exceeds the consolidation rate (the maximum sediment compaction speed under the sediment's own weight), thus inducing the development of excess pore pressure; the presence of weak (low shear strength) or weakening layers; the presence of gas such as methane that could expand under reduced hydrostatic conditions (e.g. during low

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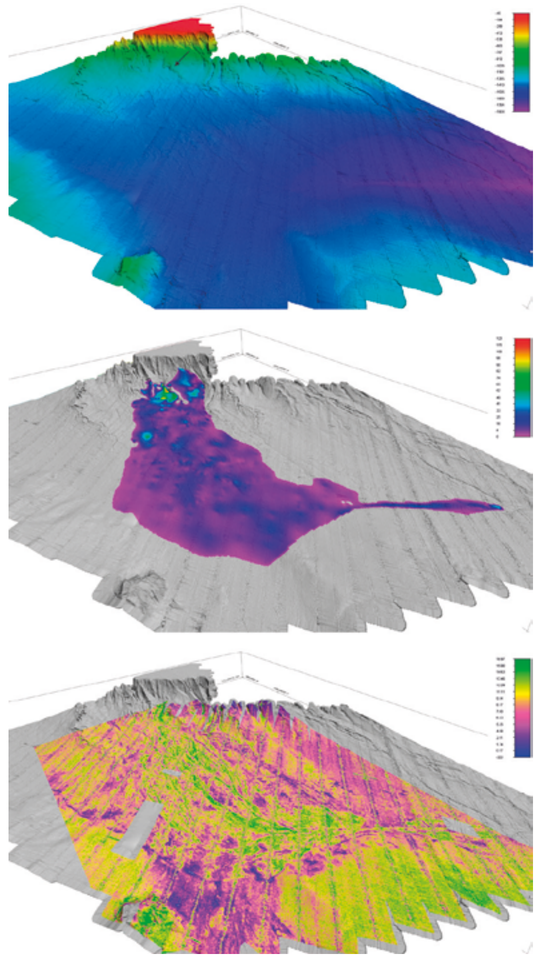

Figure 1. 3D view of the Ebro continental margin looking west (view width is ~110 km) displaying a major submarine landslide at the foot of the slope. Top view displays bathyemtric shaded relief. The 12-km-long landslide scar (arrow) is visible at the foot of the slope. The middle view displays the landslide deposit thickness, which is highest (up to 120 m thick) immediately below the scar. The landslide initially travelled downslope towards the Valencia Channel between the Ebro and Balearic slopes and then moved NW along the Valencia Channel. The bottom view displays the backscatter strength (the strength of the seafloor echo return), showing flow stream lines along the landslide path.

tides in shallow water sediments); and steepened slopes caused by geological processes such as salt diapirism and tectonics. Trigger mechanisms, on the other hand, involve a dynamic context, such as the occurrence of an earthquake or wave storm (the latter above the wave base), which induce cyclic loads on the seafloor that can liquefy the sediment. Sea level and temperature variations induced by past climate change (and perhaps climate change related to human activities in the future) have caused gas hydrate dissociation at the base of the gas hydrate stability zone and gas hydrate dissolution at the top of the gas hydrate occurrence zone (Sultan *et al.* 2004). Gas hydrate is a substance in which a water crystal–like cage structure encloses natural gas (most often methane) that is stable under relatively deep-water pressure and low temperature. The latter is determined by the hydrothermal gradient in the water column and the geothermal gradient in the sedimentary column. Dissociation and dissolution of gas hydrates in low permeability sediments induced by changes in these pressure and temperature conditions result in increased fluid pressure and sediment weakening, which may ultimately induce slope failure.

Submarine landslides on the continental margins of the Iberian Peninsula

The coasts of the Iberian Peninsula are not devoid of such hazards, and significantly large slope failures have been mapped on their continental margins. One such large slope failure occurred about 10 ka ago on the Ebro continental slope and affected 2200 km^2 of seafloor, approximately four times the size of the nearby island of Eivissa (Figure 1). This event is estimated to have generated a large tsunami, with waves exceeding 10 m in the landslide source area and on the adjacent coastlines. Landslide hazards can be represented, in a similar way to earthquakes, as magnitude vs frequency distribution curves, which relate a landslide volume to a frequency of occurrence. At the scale of the Mediterranean basin (Figure 2), such curves indicate that a landslide exceeding 1 km^3 (potentially tsunamigenic) occurs every 50 years!

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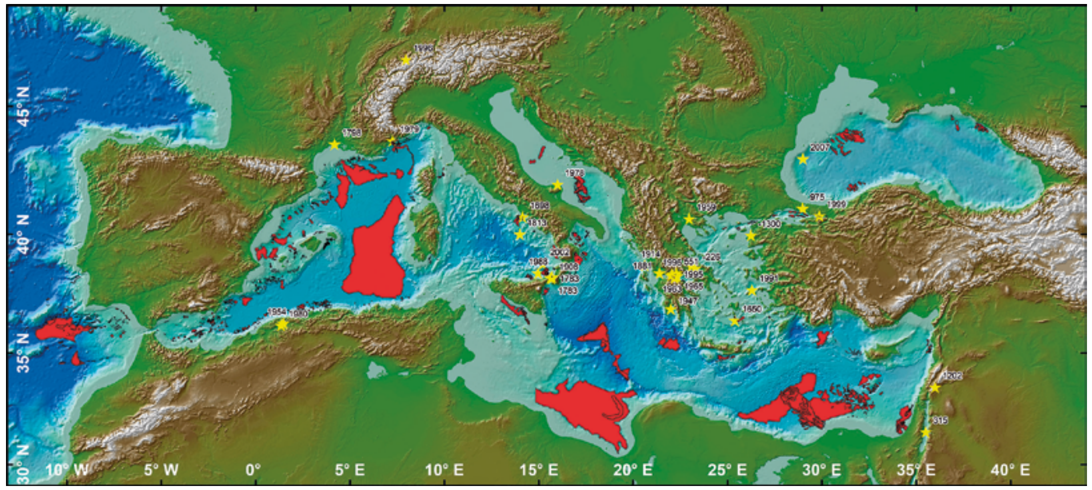

Figure 2. Map of submarine landslide (red polygons) distribution in the Mediterranean Sea on top of bathymetric shaded relief. Stars show landslide-related historic tsunami sources and year of the tsunami event.

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5.3. A shaking ocean: present and future in the study of earthquakes and tsunamis

Valentí Sallarès

With the advent and gradual acceptance of plate tectonics from the 1960s onwards, it became clear that the Solid Earth is not a fixed and static framework but a dynamic and constantly evolving system that is governed by internal forces impacting on and shaping the surface in multiple ways. The opening and closure of the oceans, the formation of mountain ranges and the occurrence of earthquakes and volcanic eruptions are all a consequence of the constant interaction between tectonic plates. One of the most spectacular and outstanding manifestations of this interaction are earthquakes, which concentrate at the tectonic faults limiting the plates. The largest and most destructive ones occur at the megathrust fault of subduction zones, where the oceanic plates slide below the continental ones at a speed similar to that of fingernail growth. This sliding is not constant but episodic: the friction between the plates makes them couple, accumulating stresses over tens or hundreds of years until they suddenly slip and release the accumulated stresses in seconds or minutes as an earthquake. The amount of slip and its spatial distribution and depth determine the shaking intensity and the resulting ground deformation.

Submarine earthquakes and tsunamis

In the case of subduction zones, most of the slip between the plates occurs under the sea, between oceanic trenches and the coastline. If the amount of slip is large enough, the associated deformation can affect the seafloor and shake the water column, causing a small-amplitude wave that propagates rapidly, at a speed similar to that of commercial aircrafts. As the wave approaches the coast, it slows down without losing much energy so it progressively grows into a tsunami, a huge mass of water that can penetrate miles inland, sweeping everything in its path (Figure 1). In the last hundred years, tsunamis have caused nearly 300,000 casualties and a countless amount of material damage, more than any other natural hazard. The growing impact associated with these events in a context of rapid urbanization and increased tourism in coastal regions has led the United Nations Office for Natural Disaster Reduction (UNDRR) to identify tsunamis as a fundamental part of the development of risk reduction policies and plans. These plans include protection of life, livelihood and health, as well as economic, physical, social and environmental assets of individuals, businesses and communities.

An important goal of these policies is to enhance basic research to identify and characterize the potential sources, improve the modelling of earthquakes and the associated tsunamis, simulate impact scenarios, develop warning systems and implement socio-administrative risk management and impact mitigation measures. Currently, the state of knowledge in basic research is quite advanced, and there is a good understanding of the physical processes that govern the generation of earthquakes and tsunamis. Much of the research effort in recent decades has been devoted to increasing the detail and accuracy of numerical simulations and gathering experimental data. The increasing availability of parallel computing resources has made it possible to numer-

Figure 1. Aerial photo of the 2004 Indonesian tsunami impact (WikiImages from Pixabay).

ically model the dynamic rupture of tectonic faults in detail, reproducing the seafloor deformation, the transmission and propagation of the wave and its impact on the coast. Furthermore, laboratory experiments have provided a great deal of information on the mechanisms of rupture, friction and slip for different materials and under different conditions.

Challenges and goals of earthquake and tsunami research

However, there are still major shortcomings in the identification and characterization of tsunamigenic submarine faults, mainly because of observational limitations. Despite the sustained technical and instrumental evolution and the numerous oceanographic surveys, large parts of the seafloor, particularly the abyssal zones surrounding ocean trenches, remain unexplored to date. Therefore, there is a significant lack of *in situ* information concerning the location and geometry of the faults and the characteristics and elastic properties of the neighbouring rocks. This forces numerical simulations of rupture and impact to be based on ad hoc models of properties that are, in general, unrealistic and oversimplified. The consequences of this basic lack of knowledge have made themselves dramatically evident on several occasions. The clearest and most recent example was the 2011 Tohoku-Oki earthquake in Japan, which was devastating for both the Japanese people and the seismological community. Even in a country that is exemplary in terms of seismological research, the simulations based on simplified assumptions of fault structure and rock properties caused the potential earthquake magnitude to be underestimated by a factor of four and the slip on the shallow portion of the megathrust fault by more than 50%. This made that the maximum height of the tsunami far exceeded the most pessimistic predictions, so it overtopped the protective walls of the Fukushima nuclear power plant, causing more than 20,000 casualties and unprecedented devastation.

This event sparked an intense scientific debate and caused well-established paradigms on seismic risk evaluation and assessment to be questioned (Lay, 2012). In particular, in recent years it has become apparent that there

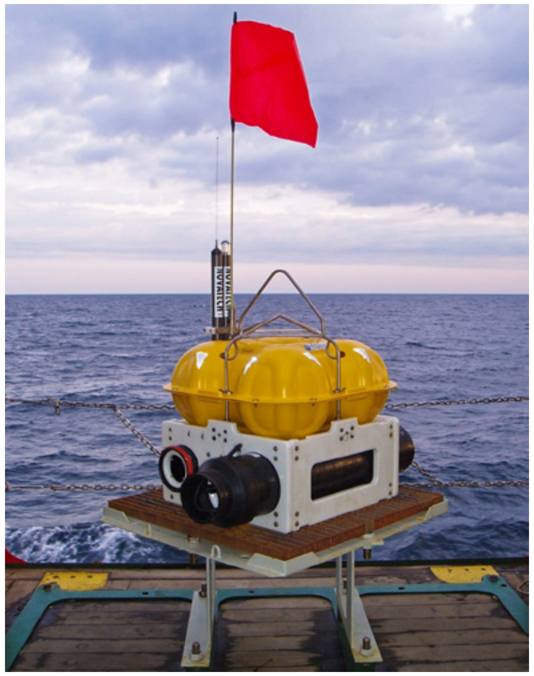

Figure 2. Ocean bottom seismometer of the Unitat de Tecnologia Marina (CSIC).

is a pressing need for improved offshore observations of seismicity and deformation in hazardous areas, and in particular in subduction zones. In Japan, this has boosted the establishment of real-time observing systems including seismographs, pressure gauges and cabled sensors, and similar initiatives are underway in other regions such as the Cascadia margin in the USA. In parallel, there has been a substantial increase in the global fleet of ocean bottom seismometers (Figure 2), especially those equipped with broad-band sensors. New instruments have been deployed on free-moving buoys, and new methodologies have been developed to turn fibre-optic submarine communication cables on seismic sensor networks. As a result, substantial progress is being made to improve our understanding of the rupture dynamics of submarine faults using offshore observations (e.g. Sallarès and Ranero, 2019). This new knowledge should lead to a more accurate prediction and assessment of the associated risks in the near future.

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5.4. Synergies for effective coastal management to deal with marine organisms proliferations

Macarena Marambio, Ainara Ballesteros, Josep-Maria Gili

Gelatinous plankton (jellyfish, ctenophores and siphonophores) form part of marine ecosystems, and many of them have inhabited our planet for hundreds of millions of years. In recent years, proliferations of some of them, particularly jellyfish, in coastal areas of the world are becoming increasingly frequent.

Jellyfish proliferation impacts

There is scientific evidence that jellyfish blooms are fostered by human pressure on coastal marine ecosystems. Some examples of this pressure are overfishing, eutrophication, species translocation, coastal habitat modification and climate change (Purcell 2012).

The presence of jellyfish in bathing areas on the Catalan coast of the Mediterranean Sea during the spring-summer season is no longer an isolated event. Every year, proliferations of jelly fish are reported in the press, bathing is restricted and the rescue services are called out to deal with stings. This causes great social alarm and has a socio-economic impact, especially on human health and tourism. Jellyfish proliferations are also a problem for fisheries and aquaculture due to fish mortality, the risk to fishermen's health and damaged nets.

Development and implementation of tools for prevention and mitigation

To deal with this problem, a specific research line on this topic was set up at the Institut de Ciències del Mar (ICM) in Barcelona. Several species of jellyfish have been bred and maintained in the ICM's Experimental Aquarium Zone (ZAE), in order to study their life cycles and growth stages and the factors that may lead to proliferations. In addition, close collaboration between researchers and government bodies responsible for coastal management has led to the development and implementation of tools for preventing and mitigating the impact of these proliferations.

Implementing these tools correctly requires cooperation between researchers, government bodies and society. It is essential for all stakeholders to be taken into account so that cost-effective and ecologically friendly solutions can be applied at all levels. The strategy proposed by the ICM is based on increasing knowledge through dissemination and educational projects; collaborative work with society through citizen science initiatives such as the iMedjelly app and the Observadores del Mar platform; joint work with government bodies such as the Catalan Water Agency, the Civil Protection of Catalonia, coastal municipalities and rescue services such as Pro-Activa and the Red Cross; experimental work in the laboratory to further knowledge on the species' biology and development; and improved first aid protocols for jellyfish stings.

After years of proposals and improvements, a network has been established along the entire Catalan coast to monitor more than 300 beaches, from the northern limit on the Costa Brava to the southern limit on the Ebro Delta. A database has been created with more than 300,000 observations of jellyfish presence and/or absence. All the work carried out has allowed

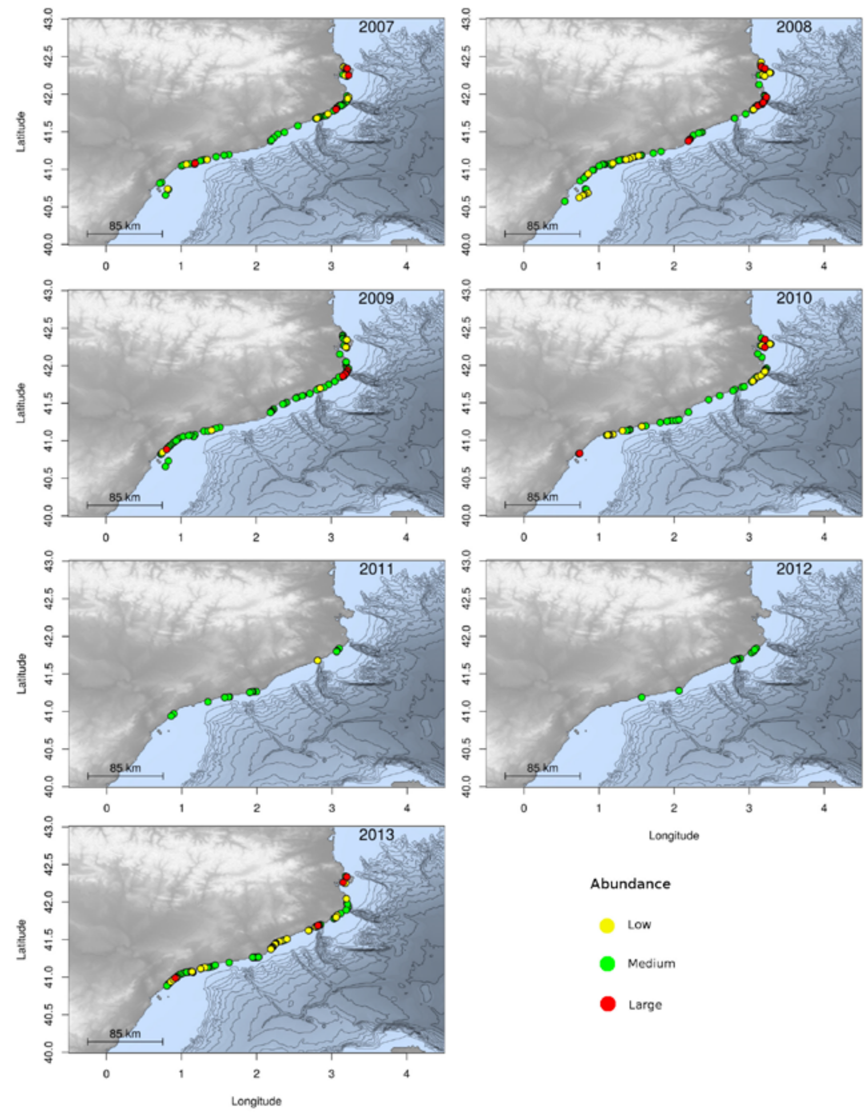

Figure 1. Spatial distribution of the species *Pelagia noctiluca* determined by monitoring studies from 2007 (upper left panel) to 2013 (lower left panel). The abundance categories are shown as: category 1, "low" (<10 individuals/beach), in yellow; category 2, "medium" (<1 individual/m^2), in green; and category 3, "high" (>1 individual/m^2), in red. (Marambio *et al.* 2021).

us to obtain very valuable results at a scientific level, such as spatio-temporal distribution maps of the main western Mediterranean jellyfish species (Figures 1 and 2) and prediction models and population analysis trends of the most important species on the Catalan coast. *Pelagia noctiluca* and *Rhizostoma pulmo* are considered to have the greatest impact due to their stinging capacity and their abundance in coastal waters. It has also been possible to describe the complete biological cycle of several jellyfish species in specialized aquariums, determine key factors in the development of the species, and establish and recommend protocols for action in cases of jellyfish presence and stings. This research makes a great contribution to knowledge on the biology and behaviour of jellyfish populations at a scientific level, and also contributes to coastal management with a real positive impact on the entire society.

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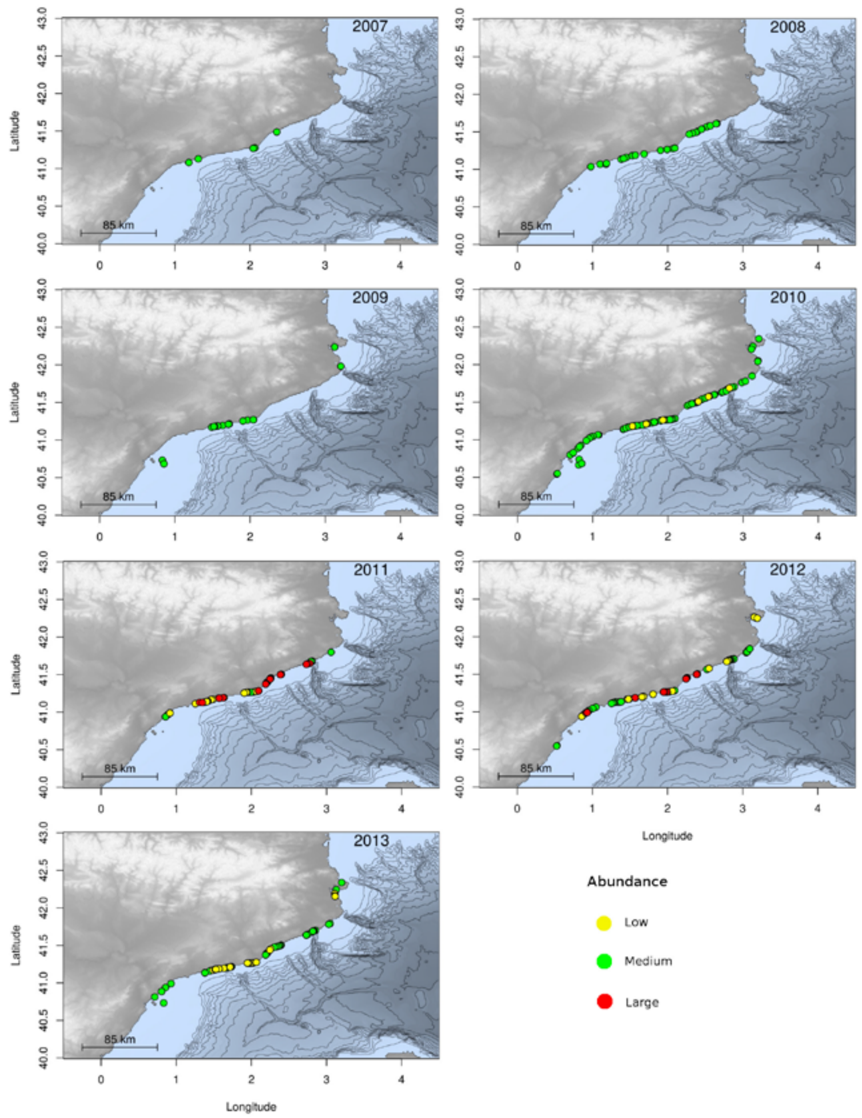

Figure 2. Spatial distribution of the species *Rhizostoma pulmo* determined by monitoring studies from 2007 (upper left panel) to 2013 (lower left panel). The abundance categories are shown as: category 1, “low” (<10 individuals/beach), in yellow; category 2, “medium” (<1 individual/m^2), in green; and category 3, “high” (>1 individual/m^2), in red. (Marambio *et al.* 2021).

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5.5. Too extreme, or not too extreme, that is the question

Marcos Portabella, Federica Polverari, Wenming Lin, Ad Stoffelen, Albert S. Rabaneda, Joe Sapp, Paul Chang, Zorana Jelenak, Giuseppe Grieco, Ana Trindade, Eugenia Makarova, Federico Cossu

How strong does the wind blow in extreme weather conditions?

This proves to be a question that is difficult to answer, but has far-reaching consequences for satellite meteorology, weather forecasting, oceanography, climate and hurricane advisories. Hurricanes are among the deadliest of the existing natural disasters, moreover causing formidable economic losses (Bevere *et al.* 2020). Accurate, short- and medium-range forecasting of their intensity and track (among others) are therefore essential to mitigate human and economic losses. In the longer range, it is also important to understand whether extreme weather conditions are becoming more extreme in a changing climate, stirring deeper waters in the ocean and hence affecting climate system dynamics. Unfortunately, tropical circulation conditions, such as *El Niño* and the Madden Julian Oscillation, are associated with large year-to-year variability in extreme wind speed distribution and their link to climate change is poorly understood, limiting our ability to determine whether the hurricane climatology is actually changing or not.

Since hurricanes are sparsely sampled, satellite instruments are in principle very useful to monitor their spatial and temporal distribution, and intensity with respect to climate change. However, to do so the stability over time in quality and quantity of satellite measurements (sampling) needs to be guaranteed. Furthermore, climate analysis requires the longest possible satellite records, but these are only useful when accurate satellite instrument inter-calibration is achieved, especially at high and extreme wind speeds (Verhoef *et al.* 2017).

To properly assess and calibrate the current and future satellite-derived extreme winds, including those from the C-band scatterometers, building a consolidated high and extreme wind reference dataset is crucial. So far, two independent *in situ* wind references have been widely used for wind calibration purposes: moored buoys and GPS drop-wind-sondes (dropsondes). A new approach has recently been presented by Polverari *et al.* (2021) to assess the consistency between these two *in-situ* datasets, for which coincident data acquisitions are rather sparse. To overcome such limitation, wind speed measurements from the Advanced Scatterometer (ASCAT) onboard Metop satellite series at 12.5 km grid resolution are used as common reference between the two *in-situ* datasets. As such, coincident measurements (collocations) from ASCAT and moored buoys are compared to coincident measurements from ASCAT and the Stepped-Frequency Microwave Radiometer (SFMR) onboard the NOAA "hurricane hunters", over the period 2009–2018. Note that, while ASCAT winds have been calibrated with buoy data, SFMR winds have been calibrated with dropsonde data.

ASCAT and buoy winds are, as expected, in good agreement up to 25 m/s, showing though a somewhat enhanced scatter between 15 and 25 m/s (not shown). The ASCAT/SFMR anal-

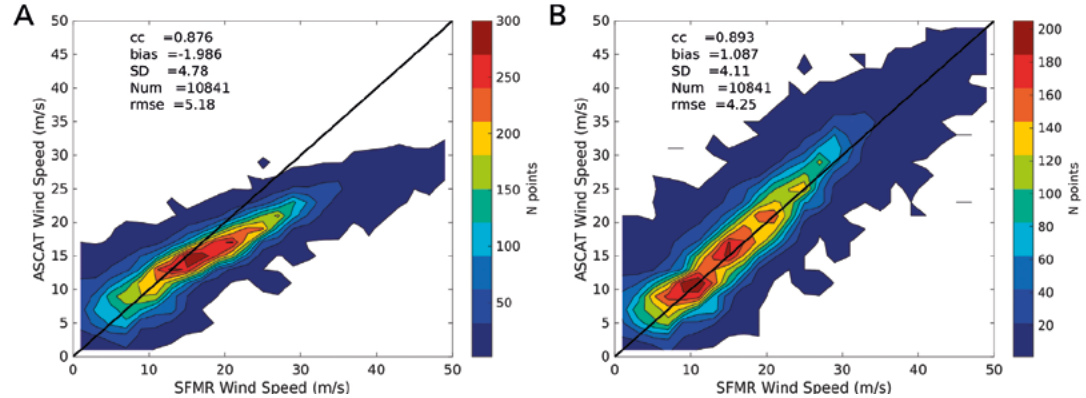

Figure 1. Two-dimensional histograms of ASCAT (onboard Metop-A and -B) and collocated SFMR wind speeds averaged over a distance of 12.5 km along track (a). In (b), ASCAT winds have been rescaled using dropsondes, i.e., using the following conversion V'(ASCAT)=0.0095x2+1.52x-7.6, with x=V(ASCAT), above 12 m/s. The statistical parameters can be found in the legend, i.e., correlation coefficient (cc), bias, standard deviation (SD), number of points (Num), root mean square error (rmse).

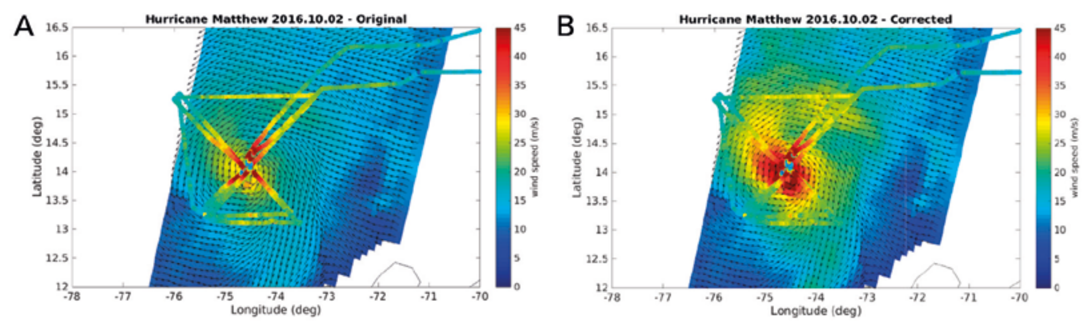

Figure 2. SFMR wind speeds (colored lines), together with (original) ASCAT buoy-scale wind speeds (A) and (corrected) ASCAT dropsonde-scale wind speeds, for a hurricane Matthew overpass.

ysis reveals an ASCAT wind underestimation for winds above 15 m/s (see Figure 1A). SFMR measurements are averaged along-track to represent winds of similar spatial resolution to that of ASCAT winds. Both SFMR (thus dropsonde) and buoy winds appear to be highly correlated (about 0.9 in both cases) with ASCAT at the high wind regime, however, they show a very different wind speed scaling. A suitable dropsonde-scale based re-calibration of ASCAT winds using averaged SFMR winds as reference can be achieved for winds up to 50 m/s (see Figure 1B) (Polverari *et al.* 2021). However, buoy and dropsonde wind scales are very different at high and extreme wind conditions. For example, while the ASCAT buoy-scale produces a 25 m/s wind (light green areas in Figure 2A), the ASCAT dropsonde-scale produces roughly a 37 m/s wind (light red areas in Figure 2B), and such differences increase exponentially with wind speed.

As such, the question is what wind source should be trusted at high and extreme wind conditions: moored buoys or dropsondes?

The best controlled resource for *in-situ* ocean wind speed calibration is the moored buoy for low, moderate and high winds. This is the main reason why the ASCAT and the global Numerical Weather Prediction models like ECMWF follow the moored buoy scale. They are validated by masts to be unbiased up to 25 m/s (within ~10%) (Stoffelen *et al.* 2020). Although buoys show lower dispersion than dropsondes at 20 m/s, there is room for further uncertainty assessment and attribution. The dropsondes in turn can fail in reporting the winds at the surface and, even when they do, the measured surface winds can be compromised by surface waves and wind gust effects. Therefore, the 10-m surface winds are usually estimated by layer-averaged winds and a correction based on the logarithmic profile is then applied to get to the surface (Uhlhorn *et al.* 2007). The main sources of uncertainty in this case are the atmospheric drag producing a strong deceleration of the dropsonde near the surface, and the accuracy of the position computation (including height) by the embedded GPS chip which has not (yet) been investigated and may cause further bias in the deceleration estimation. In other words, can the mentioned bias be responsible for the inconsistencies between dropsonde and buoy high and extreme winds?

At this stage, conclusions cannot be drawn on which high-wind reference is favorable for satellite wind calibration/validation at high and extreme wind conditions or how to consolidate both references. Further investigations are needed to better understand the sources of such differences. As per request, the so-called ASCAT dropsonde-scale winds (Figure 2B) are made available to the operational extreme wind community, which uses SFMR wind scaling (as calibrated by dropsondes) as reference for tropical cyclone characterization, monitoring, and tracking. The same approach is being used in the framework of the European Space Agency (ESA) project MAXSS to intercalibrate all other scatterometer and radiometer high and extreme wind speeds. But the question whether winds are too extreme (dropsonde-scale) or not too extreme (buoy-scale) remains for the time being.

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6. Accessible ocean

Jordi Sorribas, Arantza Ugalde, Jordi Isern, Ramiro Logares

Those of us who are lucky enough to live by the sea have incorporated it into in our daily lives. We enjoy the blue horizon and its offer of a place for meeting and leisure. Contact with the sea through physical access arouses our curiosity. It drives us to learn about it and therefore to desire to maintain a sustainable relationship with it. "An accessible ocean", one of the seven objectives of the UN Decade of Ocean Science for Sustainable Development, is therefore of paramount importance for our development and the future of our existence.

This chapter deals with the key aspects of obtaining data on the ocean and the technologies used to obtain, manage and provide access to it. It sheds light on new ways of approaching the ocean that guarantee open, equitable, participatory and barrier-free access to knowledge of seas and oceans and help incorporate it within our society. It explains how we have progressed from notes taken with pencil and paper to having billions of data stored in the cloud, open and available for use in real time, and discusses the management challenges involved in ensuring simple and reliable long-term access to these data. However, despite the importance of data for an accessible ocean, it is important to continue building and conserving physical collections. Reference biological samples and specimens are a lasting foundation of our knowledge of the ocean –testimonies of our past and present research activity that are extraordinarily useful for the future.

This chapter also deals with the platforms used for collecting data and samples, presenting an overview of how oceanographic vessels have evolved over time and of the new observation platforms that are used today. These include buoys, submarine vehicles and submarine telecommunication cables, which were not initially designed for research but open up new perspectives for observation.

One element that is becoming key for building an accessible ocean is the use of the Internet and, in particular, social media, which have become important repositories of information and a medium for the analysis of large volumes of data on the marine environment and our relation with it as a society.

We must not lose sight of the indispensable role of technicians in marine technology and the important role of women in achieving the goal of an accessible ocean. Also, citizen science, participatory monitoring systems and synergies between public research centres and private companies offer us new possibilities for expanding our knowledge and offering it to our society, ultimately making our ocean accessible.

We hope that all this will ensure continued access to knowledge of the ocean that will help keep it healthy and resilient for decades to come.

6.1. Seventy years of marine science: from notebook to cloud data

Savitri Galiana, Lucía Quirós, Elisa Berdalet, Xavier García, Emilio García-Ladona, Jordi Isern-Fontanet, Laia Viure

Data acquisition, analysis and interpretation are essential tasks for science, business and administration, and research in this field has led to major developments. At the Institut de Ciències del Mar (ICM), researchers have progressed from recording data on paper to storing them on electronic devices or in the "cloud". However, the organization, management and transfer of the data obtained –mostly thanks to public funding– still has many shortcomings. Several initiatives at the ICM are working to overcome these difficulties and organize the scientific data according to the FAIR principles that are applied internationally.

Data storage and management

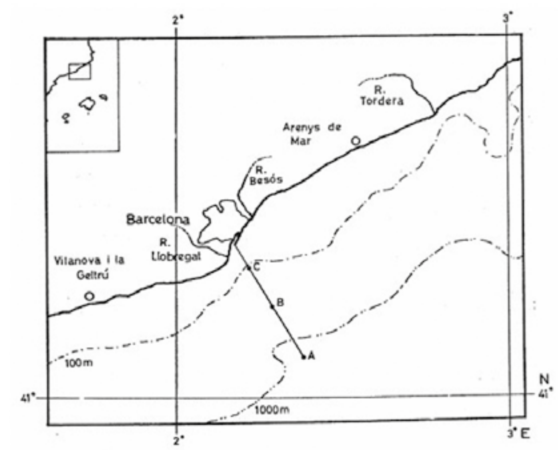
Before computers, data were recorded on paper and stored in lists, notepads and journals. Texts, charts and tables were drafted by hand and photocopied. Data stored in this way occupied a large physical volume, were slow and difficult to access and were very susceptible to deterioration due to environmental causes and accidental destruction or loss. As computer technology progressed, paper records were first replaced by punched cards that stored the data through a pattern of holes and white spaces, then by magnetic tapes and later by hard disks, floppy disks, CDs, DVDs and flash drives. Recently, thanks to advances in computing and telecommunication technologies, the concept of "cloud data" was introduced. The cloud offers an unlimited amount of data storage capacity and access anytime and anywhere that has an internet connection. The physical warehouse of the cloud consists of a network of servers, often located in different parts of the world, managed by organizations that are responsible for maintaining and protecting the physical system and guaranteeing access to the data.

As technology developed, more advanced modes of data organization and management were introduced, and the concept of databases (DBs) took shape. A database is defined as "a collection of information that is organized so that it can be easily accessed, managed and updated" (Search Data Management Tech Target 2021). Databases are usually controlled through a software known as the database management system (DBMS). A DBMS serves as an interface between the DB and its users or other programs, allowing large amounts of information to be entered, stored, retrieved and organized. The dataset and the DBMS, together with the associated applications, are called the DB system or simply the DB. Databases can be classified according to their organizational model, but the most frequent type are still the relational DBs that appeared in the 1980s. Relational DBs store and organize data in a set of tables with different types of relations between them. However, the most appropriate DB model depends on the type of data to be stored and the reason for storing it. The questions that must be answered in designing a database are i) What is the objective? ii) Who will the users be? and iii) What kind of queries should it answer? In 2016, a consortium of scientists and organizations published the principles that DB must meet for the management of big data (Wilkinson *et al.*

2016): findability, accessibility, interoperability and reusability (FAIR).

The past, present and future of data at the ICM

In the 1970s, the ICM, at that time the Instituto de Investigaciones Pesqueras, carried out the MARESME project, in which the ships R/V *Cornide de Saavedra* and R/V *García del Cid* studied the ocean circulation and characterized in particular the chemical contamination of the coast of Barcelona. Basic hydrographic, chemical and biological observations were made at three fixed oceanographic stations located in a perpendicular section on the coast. Over the course of several days of the year, the scientists sailed there with measuring instruments. Water samples were taken, current meters were installed at fixed points and buoys were thrown to drift with current meters located above and below the thermocline. The data acquired were stored in paper format and transferred through the report, also on paper, *Datos Informativos* 5, "*Datos oceanográficos frente a Barcelona*" (Salat *et al.* 1978). The data were organized in a series of tables, each table corresponding to the measurements made in a certain position and on a certain day (Figure 1). At that time, to analyse the data and be able to find the value of a parameter at a certain depth, position and day, you had to have access to this report, review all the tables,



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PROF	TI	TEMP	SALN	SG-T	VESP	OXIG	NO3	SIO4	PO4	CL-A
0	3	17.94	37.847	27.487	97.325	5.96	.00	.00	.00	
5	2	17.92	37.827	27.477	97.324	6.05	.00	.00	.00	
10	2	17.88	37.843	27.499	97.320	5.93	.00	.00	.00	
25	2	17.20	37.962	27.759	97.289	5.78	.00	.00	.00	
50	2	16.47	38.118	28.055	97.250	5.78	.00	.70	.00	
75	2	15.89	38.104	28.181	97.228	5.80	.45	.70	.09	
100	1	15.09	38.156	28.405	97.197	5.83	1.29	2.60	.09	
150	1	13.37	38.300	28.893	97.129	5.57	4.16	3.70	.27	
200	1	13.24	38.392	28.992	97.099	5.30	5.91	4.70	.17	
250	1	13.26	38.444	29.028	97.074	4.98	6.29	5.90	.23	
300	3	13.67	38.460	28.953	97.061	5.10	7.54	6.40	.32	

Figure 1. An example of storage and transfer of data in the 1970s by the Instituto de Investigaciones Pesqueras, today the Institut de Ciències del Mar. Top left, cover of the report. Top right, location map of the oceanographic stations. Bottom, a data table from station number 87 recorded on 10 November 1975 from the *Datos Informativos* number 5 report of the Instituto de Investigaciones Pesqueras (Salat *et al.* 1978).

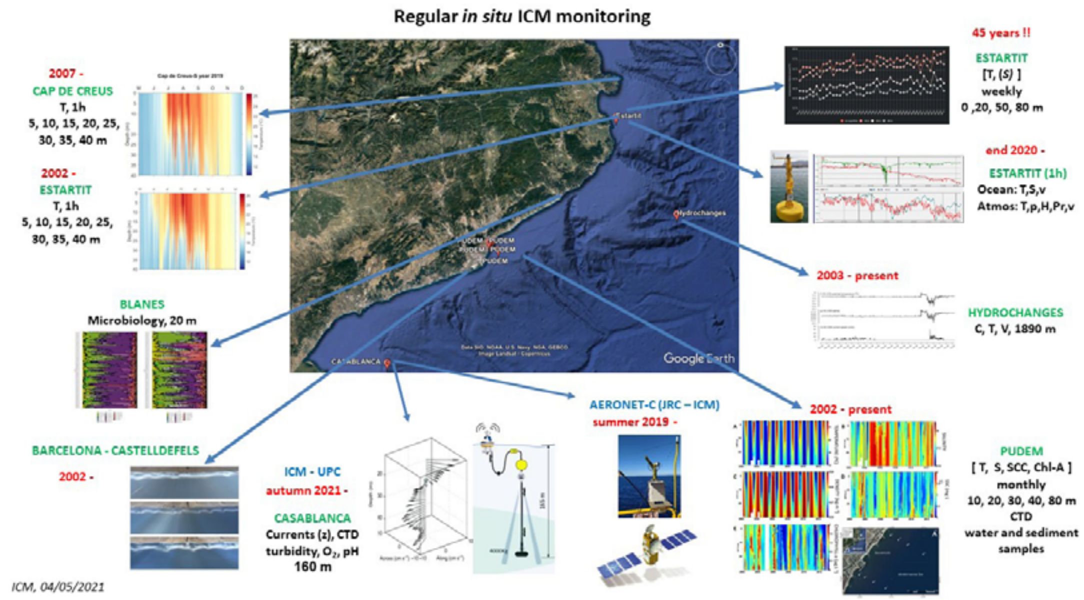

Figure 2. The current panorama of data acquired by the ICM for monitoring the marine environment on the Catalan coast. It is planned to include them in DBs, which will reinforce multidisciplinary studies.

and manually extract the values of interest. Graphs were also drafted manually.

Today, data acquisition during sea-going campaigns, such as Spurs in 2013, has been automated to levels that were unimaginable 40 years ago. The objective of this cruise was to study the oceanographic processes responsible for the formation and maintenance of maximum salinity at the centre of the subtropical shift of the North Atlantic. The researchers used state-of-the-art instrumentation such as drift buoys designed and built at the ICM, which transmitted surface position, temperature and salinity data from the sea via satellite every hour. Some of these buoys were recovered three years later in different parts of the planet, so they were transmitting data in real time every hour for years.

Despite advancements in the data acquisition technology used at the ICM and the possibility of storing data on hard drives, local servers and data clouds, its management and transfer remain quite limited. Most scientists still have their data files stored with specific criteria (typical of the study but not standardized) on their hard drives or servers, without having them organized in a DB. In the coming years, it is expected that more and more machines will deal with the acquisition and processing of data, making marine sciences a discipline based on big data. The European Marine Board Expert Working Group on big data recently launched a series of recommendations to promote the implementation of FAIR principles in the field of marine sciences (Guidi *et al.* 2020). At the ICM, initiatives such as the Xarxa Marítima de Catalunya and IcatMar are developing DBs for fishing and map viewers that allow for better management of fishing resources. In addition, the data capitalization projects SHAREMED and MED OSMoSIS of the Interreg Med programme are working to include data or metadata (descriptive information on the characteristics of the data) of ICM researchers in DBs (Figure 2). This will allow the information to be organized in a much more homogeneous way, guarantee the quality of the data and make them much easier to access, update and transfer. In other words, the FAIR principles will be followed, and this will open up new possibilities for multidisciplinary studies that provide a better understanding of the ocean and its changes.

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DOI: https://doi.org/10.20350/digitalCSIC/14108

6.2. Technical support to science

Joel Sans, Arturo Castellón, Jordi Sorribas

It seems a long time since 1971, when the oceanographic research vessel *Cornide de Saavedra* embarked an IBM 1130 computer for the first time to process continuous data of temperature, salinity and chlorophyll of the sea surface. This practice, which is so familiar today, changed the way we look at oceanography. Fifty years have passed since then.

Undoubtedly, the fields of technology and science run in parallel, both feeding on the results of the other to eliminate obstacles to new learning and facilitate their ascent to new knowledge. However, between the two fields, there is a third actor that stands as an intermediary. Between the material resources provided by technology in the form of platforms and scientific equipment and the result of the research activity provided by science, there lies the field of technique. Its mastery of technology and its knowledge of the field of study make it an essential tool for work both in laboratories and in the field. The Unitat de Tecnologia Marina (UTM) is an important agent of technique in the marine field in Spain.

History of the Unitat de Tecnologia Marina

Aware of the importance of technique in the field of marine sciences, the Oceanographic Vessel Management Unit (UGBO) was created in 1992 with the purpose of providing technical and logistical support to the research projects carried out on board the R/V *Hespérides* and the R/V *García del Cid*.

In 1999, the UGBO's range of action was expanded and it obtained the integral management of the Juan Carlos I Spanish Antarctic Station. The UGBO was resized and acquired a new magnitude as the Unit for the Management of Oceanographic Vessels and Polar Facilities (UGBOIP). Finally, in 2000 the UGBOIP became what we know today as the Unitat de Tecnologia Marina (UTM).

In 2007 the UTM took on a new dimension and consolidated itself as a bridge between the scientific community it serves and the research platforms it manages. Thanks to great efforts, a new benchmark in Spanish oceanographic research was introduced: the R/V *Sarmiento de Gamboa*.

In 2010, the remodelling works of the Juan Carlos I Spanish Antarctic Station began. The economic crisis that hit the country made its construction difficult and seriously delayed the completion of the work. However, in 2017 the remodelling se was completed, marking an important achievement for the polar science.

Apparently, in 2020 the UTM faced new challenges with the integration of the Instituto Español de Oceanografía within the structure of the CSIC. The UTM expanded its administrative and economic management capacity, enhanced important and strategic functional

Figure 1. R/V *Sarmiento de Gamboa* during the deployment of Ifremer ROV Victor-6000.

Figure 2. Austral summer at Juan Carlos I Spanish Antarctic Base. © Javier Urbó

areas that would facilitate the comprehensive management of the entire fleet and reinforced the technical and technological base of marine research.

With 30 years of technical activity, the UTM has become a major player in the management of marine and polar technique in the Spanish Oceanographic Fleet (ICTS FLOTA) and in Antarctica.

What does the future hold?

With the new and renovated facilities, the UTM aspires not only to offer a fully consolidated technical service but also to be a key player in technological development and innovation projects in the field of marine and polar technologies.

The UTM's technical area is undoubtedly a source of inspiration that is absolutely necessary for development, as it has enormous experience and extensive knowledge and training within its scope of action. This great potential must be transferred not only to field activities but also to development and innovation. Failure to do so would be a clear waste of the best resources available to the UTM.

In the short term, the UTM must develop engineering projects that are intended to meet an unsatisfied need. The activity focuses on developing solutions that do not exist on the market. If the market does provide the solution, the UTM can analyse how far it is compatible with the existing need, and consequently design and execute a bridge solution between the two.

For longer-term strategies, the UTM must create its own lines of technological research that involve improving technology, methodology and technical implementation in observations *in situ* and analysis. It must be aware of the state of the art and trends of marine science and technology. It must also participate and collaborate closely with other groups and lines of national and international technological research, technology centres, universities and industry that pursue the same purpose and anticipate the needs of scientific teams as an investment for the future. Finally, the UTM must further exploit its position and the facilities it manages as a strategic factor in marine sciences.

Never have marine sciences and technologies been so necessary as now. Technological development is an asset that the UTM must and wants to explore, develop, share and make available to the community it serves. It is endorsed by its 56 technicians, the 568 cruises in which it has participated and the 1,303,573 nautical miles it has sailed.

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6.3. Geological collections: a scientific heritage

David Casas, Gemma Ercilla, Belén Alonso, Ferran Estrada

The study of the seabed is a complex goal because of the technical difficulty of accessing and recording underwater environments, and especially deep-sea areas. It is mainly achieved by two methods: recording acoustic and seismic data (bathymetry and seismic profiles), which offer indirect observations of the morphology and the tectono-sedimentary framework; and taking sediment samples, vertical columns several metres long (sediment cores), which provide information on the composition and age of the deposits and the processes that generated them.

From the record to the repository. From the repository to the resource

Technical and economic progress since the 1980s has favoured the access of the scientific community to better oceanographic vessels equipped with better instrumentation. However, the adverse environmental conditions and the high economic cost of working at sea mean that each square kilometre of acoustic data, each kilometre of seismic data and each metre of sedimentary column are of enormous value because it is unlikely that they will be obtained again. Therefore, in addition to their historical value, the collections must be understood as a valuable scientific and socio-economic resource, and the utmost care must be taken in cataloguing and conserving them.

Geological data collections are aligned strategically with the past, present and future needs of the scientific community. Thanks to these collections, historical data from different geological environments that have been studied with very diverse standards and purposes are made accessible for future scientific needs. They are a resource from which a huge amount of new knowledge can be extracted using new technologies.

Sediment cores and seismic records are key resources for future research on topics such as global and climate change, marine geological hazards, pollution control, habitat mapping, submarine mining exploration and offshore engineering. Disciplines such as paleoclimatology and palaeoceanography decode the information preserved from past climates and ocean circulation in marine sediments. Understanding these changes helps to generate models that can project them into the future.

The geological collections of the Institut de Ciències del Mar are an outstanding scientific heritage of the CSIC that is made up of data sets collected by research projects dedicated to exploring and exploiting the sea bottom for decades. The collection includes two large groups of records: 1) a set of more than 1,000 sediment cores from the seabed and sub-bottom, as well as

Figure 1. Partial image of the ICM-CSIC core repository.

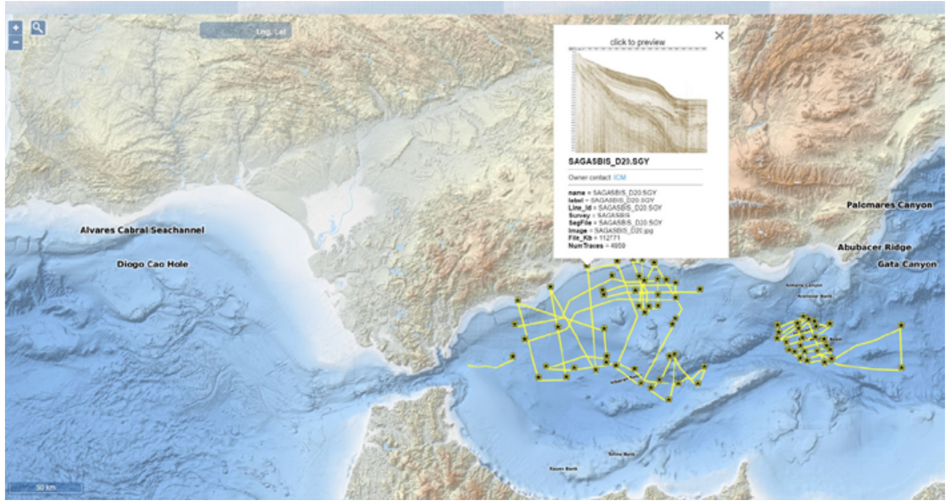

Figure 2. Database of the geological collections of the ICM-CSIC (http://gma.icm.csic.es/en/data).

data and derived products such as photographs, x-radiographs and analytical (textural and compositional) results from subsamples; and 2) an extensive database of over 100,000 km of seismic profiles with different resolutions, both on paper and in analogue and digital format.

Most of the sediment cores from the collection are stored in a cold room that constitutes the core repository (Figure 1). Other types of samples are stored at room temperature. In addition, the ICM has several facilities for analysing samples and cores and for working with seismic profiles.

The data in the collection come from the seas and oceans where ICM-CSIC researchers have worked, from Antarctica to the Pacific and Atlantic, although the data density is especially high for the western Mediterranean. The metadata identifying the elements of the collection are also published in an open access geoportal (Figure 2).

Once the collected data have been exploited by the scientific teams, they are incorporated into the repository following a protocol for quality control, preservation and accessibility of metadata.

It is intended that the ICM's geological collections will evolve to become an interconnected repository with multiple sources for visualization, analysis and interpretation. This evolution requires the implementation of a data management system that allows the retrieval of stored data and generates queries remotely, giving access to both original digital and scanned images. This goal also requires the development of tools to access descriptions and visualizations of data for analysis. This step is especially important when, for example, it is intended to build a regional database consisting of hundreds of sediment cores with their corresponding analytical data, whether continuous or related to sediment subsamples.

Managing a great diversity of data to achieve standardization is in itself a challenge, but it is essential for the geological collections of the ICM-CSIC. The repository must be able to connect, communicate and complement with existing databases to achieve its maximum value. The link with other regional, national or international repositories such as EMODnet (https://emodnet.eu; Thierry *et al.* 2019) should be mandatory.

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6.4. Biological Reference Collections: a record of the past and present that is useful for the future

Pere Abelló, Elena Guerrero, Ricardo Santos-Bethencourt

The Biological Reference Collections of the Institut de Ciències del Mar (Figure 1) were created in response to the need to catalogue and have at hand specimens that could act as referents of the marine fauna studied by the scientists of the former Instituto de Investigaciones Pesqueras, who were known from the 1960s to the 1990s as *Pesqueres*. The main geographic study area was then the Mediterranean coast, and the preferential zoological groups were the species of fisheries interest. From the beginning, however, great importance was given to biological diversity, because the departments of Zoology, Botany, Microbiology and Genetics of the University of Barcelona have always given a high degree of importance to the study of biological diversity and its relationship with the environment (ecology).

Figure 1. Biological Reference Collections (CBR-ICM). One of the corridors with catalogued specimens kept in ethanol. Each container has labelled information on the catalogue number, species name, location in the collection and other useful internal information, in addition to the database reference. (Photo: Elena Guerrero, CBR-ICM).

The premise that exploited populations cannot be studied and managed only using fisheries-dependent information has always been considered very important. The interactions with the environment, predator-prey relationships, associated non-target species and physical oceanography are essential for proper management. The failure of species-specific fisheries management based only on fisheries-dependent information showed that management focused mainly on target species only make some sense in ecosystems based on the presence of just a few species with linear predator-prey relationships, which is most often not the case. In biodiversity-rich biological communities, on the other hand, the stability of the system depends on the overall relationships among the species. Therefore, we must obtain a good knowledge not only of the target species but also of the overall biological and physical system of the ecosystems and their temporal variability. The need to know and identify the species and their life-history stages (larvae, juveniles, males, females, etc.) led to the creation of the reference collections of fish and other zoological groups of fishery interest, such as crustaceans and cephalopods, as well as the associated fauna. The pioneers of this stage were the ichthyologists Jaume Rucabado, Domènec Lloris and Conchita Allué.

The exemplars of reference

Based on the premise of the existence of different species (without entering into the debate on the concept of species), it was con-

Opening
Clean ocean
Healthy and resilient ocean
Productive ocean
Predictable ocean
Safe ocean
Accessible ocean
Inspiring and engaging ocean
Indexes

From notebook to cloud data
Technical support to science
Geological collections
Biological Reference Collections
Gender equality in marine research
A new generation of research vessels
Observing the evolution of a water particle
Autonomous platforms in oceanography
Oceanographic cruise data management
Sensing the seafloor with fibre-optic cables
Jellyfish prevention and post-sting tools
The emergence of iEcology
Citizen science and participatory monitoring systems

Table 1. Number of records, species, type specimens and holotypes catalogued in the Biological Reference Collections (CBR-ICM) by main phyla and total. Information available in the database on May 2021. Contents are regularly updated and published in the Global Biodiversity Information Facility (GBIF). Others are Annelida, Cnidaria, Echinodermata, Nemertea, Sipuncula, Bacillariophyta, Ciliophora and Perkinsozoa.

	Phylum				
	Chordata	Arthropoda	Mollusca	Others	Total
N. of registers	14,791	20,310	1,814	1,308	38,223
N. of species	3,551	1,046	285	50	4,932
N. of types	63	200	16	4	283
N. of holotypes	11	41	3	3	58

sidered necessary to have at hand reference individuals of the species of fishery interest and other associated fauna. We know, for example, that there are two species of red mullet along our Mediterranean coasts. Therefore, we need to have individuals of both species to act as a morphological reference of each one so that we can identify them properly. The same is true of hake. There is just one species of hake in the Mediterranean, so little effort would be needed to obtain reference individuals. However, all species have males, females and juveniles, often with different morphologies, and larvae that hardly ever resemble the adult individuals. The Spanish fisheries were also increasing their geographical range to the Atlantic coasts of Europe and Africa. It was therefore necessary to document the species that were exploited in each region. Fisheries research cruises were performed with both research ships and freezer trawlers, especially along the coasts of the Western Sahara, Namibia and South Africa, where, for example, non-experts find it difficult to identify the several different species of hake. During that period, a great effort was made to document not only the target species of the fishery but also the associated fauna. The discovery of new species for science was one of the strong points and the value-added components of the reference collections. In addition to fishes, fish otoliths began to be collected as the basis for most fish age estimations used for fishery management, among other scientific uses.

Collections today

Our collections currently contain a total of 38,223 records, with a total de 4,932 species, mainly of adult and juvenile fish and larvae (ichthyoplankton), fish otoliths, crustaceans (shrimps, crabs, lobsters, mantis shrimps, cumaceans, mysids, isopods and amphipods), molluscs (octopuses, squids, bivalves and gastropods), echinoderms (seastars, urchins and holothurians) and other zoological groups that are fewer in volume but no less important for the functioning of the marine ecosystems. Our collections also manage a total of 283 type specimens, of which 58 are holotypes, the specimens used to first describe the morphology of a species that is new to science (Table 1).

Specific mention must be made of the Zariquiey Collection, a donation of the Zariquiey family to the ICM that constituted the basis of faunistic knowledge on decapod crustaceans, not only around the Iberian Peninsula but also in the whole Mediterranean Sea.

One of the most important functions of the Collections is to provide the option and the infrastructure for researchers from all over the world to carry out stays in our facilities to study the specimens, as well as to provide specimens loans. In the last few years, the collections are also becoming important as repositories of DNA for genetic studies on phylogeny, population genetics and evolution, thus helping to increase the knowledge of the Tree of Life. They also generate a continuous flow of important scientific papers that increase and solidify the base of biodiversity-based science. We consider that our collections, which are fully available on the internet and are coordinated internationally, constitute a research infrastructure and an important historical, cultural, scientific and natural heritage for use in the past and present, and hopefully also in the future.

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6.5. The ICM's commitment to gender equality in marine research

Esther Garcés, Silvia Donoso, Elena Torrecilla, Janire Salazar, Sara Soto, Clara Cardelús, Maria Gracia Puga, Queralt Güell Bujons, Cristina González Haro, Josep L. Pelegrí, Andrea G. Bravo, Pere Puig, Mercedes Blázquez, Belén Alonso

Despite the drive towards equality between women and men in research institutions in recent years and the progress that has been made, there is still a long road ahead. Science is still associated with the male image, and women's work and contributions are often invisible. Like many other spheres of society, research institutions contribute to the structural re(production) of gender inequalities.

Women and men each tend to have more presence in certain scientific fields, with the horizontal segregation that this involves. Furthermore, the "glass ceiling" (the invisible barrier that hinders women's access to the highest levels of decision-making or responsibility, limiting their professional careers) causes vertical segregation. Staying in research is an obstacle course in which there is a constant trickle of skills and talents, which is exacerbated for women. Moreover, research often seems blind to the gender dimension in its approach, content and analysis.

Dealing with this situation requires institutional changes at many levels. Nowadays, it is a priority on the agendas of many international organizations. In this sense, the European Commission aims for the gender dimension to be fully integrated into Horizon Europe's research projects, and the European Research Area also establishes as a priority that gender equality and the gender perspective be integrated into research. Likewise, integrate gender equality in the field of marine research is a requirement set by the UN in the framework of the Decade of Ocean Science for Sustainable Development.

Gender equality as a guiding principle of the ICM

As a centre of excellence in marine research, the Institut de Ciències del Mar (ICM) is fully aligned with the commitment to gender equality. The people who work at the ICM carry out our work with a concern for knowledge of the marine environment and a holistic vision, and we are prepared for today's challenges. As a result of this pioneering position and creative outlook in the study of the oceans, our institution also has a great responsibility to society. Our commitment as a public-funded research institution is to achieve scientific excellence in the marine field by promoting the values of respect, equality, diversity, transparency, and collaboration (Figure 1).

Since 2017, the ICM has an Equality Task Force, which has become a focus for reflection, debate, training, generation of alliances and actions. Some of its work has been aimed at giving visibility to the work and creativity of female researchers and technicians, providing opportunities for participation, identifying expressions of inequality, and proposing improvement measures, identifying and deploying good practices, and bringing science closer to schools by offering female role models[1].

Figure 1. A sea of diversity. Illustration by Vanessa Donoso

This process took a qualitative leap forward by obtaining funding for two European projects[(2)] aimed at promoting gender equality in innovation and research. As a result of these initiatives, for the first time, the ICM has a Gender Equality Plan[(3)] at the institutional level.

The ICM's Gender Equality Plan

Before the drafting of the Plan, a diagnosis was carried out to establish the specific situation of women and men regarding equal treatment and opportunities, as well as to identify inequality gaps and the factors that produce them. The diagnosis has led to an awareness of situations of inequality and discrimination based on gender and revealed the possibility of making informed decisions to reverse this situation. The Plan prioritizes objectives and results and defines a set of measures to achieve them in various fields of action, including among others, career development, training in gender equality, organization of working time, co-responsibility and work-life balance, gender equality in the functional and organizational structures of the center, and the inclusion of gender in research and innovation.

The Plan, which will be implemented over the next two years, includes cross-cutting actions that need to be anchored in institutional policies and positive action measures aimed at correcting identified situations of inequality. It is also a dynamic document that can be adapted to meet new challenges and future contexts. To evaluate the impact of the Plan, a set of indicators is available to verify the achievement of results. The Plan is the institutional roadmap for equality and has been endowed with the necessary resources for its effective implementation.

For the Equality Task Force, the journey so far has been a very enriching process and at the same time a constant challenge. We are convinced that the Plan will be a revulsivet for the ICM. It will undoubtedly have positive effects not only among women, by reducing gaps and eliminating gender biases, but also among all staff, with the improvement of team motivation, the retention (and recruitment) of qualified professionals and a new impulse for corporate social responsibility.

The Plan also presents us with the new challenge of rethinking our marine research by incorporating the gender dimension and intersectionality. It will provide a stimulus that will help the ICM to achieving a more inclusive, diverse and transformative ocean science and to become a benchmark marine research centre for new generations.

(1) The ICM was recognized with a runner-up prize in the Distintivo de Igualdad (Equality Award) of the CSIC in the 2020 call for applications.

(2) LeTSGEPS and RESBIOS are projects funded by the European Commission's Horizon 2020 SwafS programme. LeTSGEPs, Leading Towards Sustainable Gender Equality Plans in research institutions, Grant Agreement n° 873072. RESBIOS, RESponsible research and innovation grounding practices in BIOsciences, Grant Agreement Nº872146. We have also actively participated in the SwafS project ACT, Promoting Communities of Practice to advance knowledge, collaborative learning and institutional change on gender equality in the European Research Area, Grant Agreement n° 788204.

(3) http://bit.ly/GEP-ICM-2021

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6.6. A new generation of research vessels

Jordi Sorribas, Arturo Castellón

For more than two centuries we have used boats to observe the oceans, but the conception of oceanographic vessels as we know them today is relatively recent. We have an authentic fleet of highly technical oceanographic research vessels that are highly specialized and capable of deploying a multitude of sensors and measurement and sampling devices. Although we use airborne observation techniques, with sophisticated sensors mounted on satellites that provide us with information from the "skin" of the oceans synoptically, networks of underwater sensors capable of monitoring a large number of parameters and transmitting the data to the internet in real time, autonomous vehicles and measurement stations, and even sensors mounted on the back of marine animals, research vessels remain today a fundamental platform for the marine scientist's work.

In Europe alone (European Marine Board 2020), the 23 countries have 99 oceanographic vessels of different sizes, from small coastal vessels to large ocean vessels and even icebreakers. These vessels are owned and managed by 62 different institutions, of which the Spanish National Council for Scientific Research is one. Through through the Unitat de Tecnologia Marina, it manages part of the Spanish Oceanographic Fleet made up of nine vessels, which constitutes one of the nodes of the Spanish Map of Singular Scientific and Technical Infrastructures (ICTS). These are considered cutting-edge facilities that provide services for research of the highest quality, as well as for the transmission, exchange and preservation of knowledge, technology transfer and the promotion of innovation.

The research vessel

A key element of the Spanish science and technology system is the fleet of oceanographic vessels, thanks to which it is possible to carry out high-quality marine science within the international context. More and more marine research groups made up of scientists and technologists from various institutions and countries are using our ships as platforms for the multidisciplinary study of a marine environment that cannot be understood without analysing the complex relationships within it. This cross-cutting approach to the study of the marine environment has turned oceanographic vessels into multi-purpose resources. Their structural design, the distribution of the interior spaces (laboratories, decks and holds), the physical elements to support the sampling (gantries, cranes, winches, gondolas, drop keels, etc.), the silent and efficient propulsion and the sophisticated systems of navigation and information (dynamic positioning, remote control, unattended machines, etc.) characterize and distinguish them from any other type of ship.

The construction of a ship in a shipyard, where the hull is assembled from welded metal pieces, is only part of the process. The design and construction of an oceanographic vessel entails a thorough interaction between the institutions that will manage them and the shipyards that will build and maintain them throughout a life cycle estimated at more than 25 years. The ships must be suitable for adapting to the demands of new research techniques that will appear in the future. Fortunately, thanks to the effort and vision of our naval sector and the support of the administrations, Spanish shipyards are very well positioned in the sector of construction and maintenance of oceanographic vessels. Our shipyards have built many of the newly built oceanographic vessels launched in the last ten years in Europe (the United Kingdom, Norway and Sweden) and South America (Peru and Argentina).

Floating laboratories

All current oceanographic vessels have common characteristics, because they almost all carry out the same type of sampling. Though there are a few cultural differences and the evolution from previous ships marks the characteristics of the new ones, some elements, spaces and pieces of equipment are essential for marine research today. Initially, fishing boats were adapted to deploy equipment such as bathythermographs, but later CTDs, plankton nets (bongos), winches, davits and poles and then A-frames appeared. An example of this is the R/V *García del Cid*, which was launched in 1979 as a deep-sea fishing boat, with its trawl winches and its whip mast, but it was transformed into a multi-purpose vessel in 1989 through the incorporation of an aft A-frame and the elimination of its aft ramp (Figure 1). Acoustics also began to be used in fishing and has finally become the marine technology par excellence. Now multiple transducers with a variety of purposes populate the keel of an oceanographic vessel.

Sampling is carried out with the boat stopped (in station) or by trawling with the boat in motion. All current oceanographic vessels therefore have two stages, one to the starboard side and one to the stern, in addition to the frames and winches (and cables) for servicing these operations. Though we continue to release deck equipment using a cable, the characteristics of the equipment have evolved. The addition of remotely operated vehicles and autonomous underwater vehicles has added new types of manoeuvres to deploy and recover them from the sea: launch and recovery systems. The R/V *Sarmiento de Gamboa* (Figure 2) was a turning point in which the experience learned on the previous ships was brought together.

When a boat is designed, the latest construction standards are applied. The engines always follow the latest developments without risking untested technologies. It is here and in the hull design that the shipyard must offer its best trade. However, in the general layout, scientific spaces (laboratories), and especially in the deck layout, the client's experience comes into play. As when designing a home, we know where we need the various facilities and what we want the boat for. The R/V *Sarmiento de Gamboa* was de-

Figure 1. R/V *García del Cid*.

Figure 2. Cable stowage al R/V *Sarmiento de Gamboa*.

signed to obtain a flexible boat that would cater for both the known scenarios and adapt to the scenarios to come. New manoeuvres and services must sometimes be implemented in the short term. The distribution of equipment on deck is also determined taking into account the possibility of mobile equipment that is installed and uninstalled according to the type of sampling (Duduyer *et al.* 2015). This makes the mobilization and demobilization periods (rigging of the ship) longer and more expensive and, in some cases, trials and tests have to be carried out in port or at sea to certify the manoeuvres: all manoeuvres must be registered and approved by the responsible staff and any incidents must be documented. The classic marine technology, with its knots, shackles, swivels and thimbles, still plays a role here.

Oceanographic vessels have expanded their possibilities for conducting analytics to the extent that their laboratories have no reason to envy those existing on land. Spectrophotometers and fluorimeters, cytometers, laminar flow hoods and stoves are common elements, and research groups continue to install new analytical equipment. More and more disciplines include incubation and onboard experimentation, which sometimes demand new facilities and services. The number of people to embark is therefore also a limiting factor in oceanographic campaigns, requiring the adaptation of habitability and the associated services. Finally, communications and information technologies have substantially changed the development of cruises and their research. Data obtained on board can be sent to laboratories on the ground where they are processed. In turn, information on meteorology and temperature, salinity and fluorescence fields obtained by satellite technology and model processing can be sent to the ship. The ship's laboratory grows big with this processing of information, and new jobs and associated disciplines appear. On an oceanographic ship a variety of marine technologies are implemented, including navigation, mechanical propulsion, manoeuvres on deck, sampling, analytics, experimentation and acoustics.

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6.7. Observing the evolution of a water particle

Joaquín Salvador, Josep L. Pelegrí

The ocean waters flow continuously, never stopping, with a variability that takes place at very different spatial and temporal scales. At some point it may seem that their motion is limited to a small area, but nothing is further from reality. The ocean is unique and global, and all waters and ecosystems are connected. One of the essential elements for understanding the functioning of the oceans is precisely our ability to track the movement of the fluid patches that connect the entire marine world, including the physical environments and the organisms and communities that inhabit them.

As technology advances, techniques for observing the movement of the marine fluid have developed. Remote observation provides image sequences of various sea surface properties (e.g. colour, temperature, salinity and mean sea level height) that allow the movement and distribution of water masses to be inferred (NOAA 2021). New communication technologies (Iridium, Globalstar, Orbcomm, GPS, Glonnas, among others) allow this information, and all other data collected from the ocean in many ways, to reach us practically in real time. All this allows predictive models of the state of the oceans to provide us with a fairly accurate vision of the marine environment. An example of this is the real-time and open-format marine services provided by the European Union (Copernicus 2021).

In this essay we will describe the techniques of direct observation of the movement of the water parcels –what we usually call the Lagrangian view of the behaviour of the fluid. We will start with a brief historical review of these observation techniques and then focus on the main observation programmes that use autonomous systems that drift with the fluid.

Historical evolution in the measurement of currents

Marine currents have always been of great importance to sailors, and many different devices have been used to measure them. One of the first techniques used by sailors was the log line, a knotted line with a triangular piece of wood attached to the end that provided an approximate measure of navigation speed. With the boat at anchor, the line could be used to obtain the speed of the surface current. Despite being a very rudimentary method, it allowed the United States Hydrographic Service to make a fairly accurate description of the movement of surface waters in the Gulf Stream in the late 19th century.

During the British Challenger expedition (December 1872 to May 1876), the “current drogue” was used. It consisted of a blade structure that was ballasted and attached by a rope to another wooden structure on the surface. This shallow buoy barely protruded from the water to prevent the wind from blowing it off, and it was flagged so that it could be more easily located. This method of measuring currents was used for many years with varying drogue sizes and at depths ranging from the surface layers to several hundred metres. Its trajectory could be described by referencing its position with landmarks when it was used near the coast and with astronomical references when it was used in the open sea.

These methods evolved throughout the 20th century with the appearance of radio communications, which allowed the positions of these drifters to be established more efficiently without having to follow the buoy. At the end of the last century, with satellite communications and GPS, drifting buoys underwent a fundamental advance.

Surface drifters and deep floats

There are many types of designs meant to move aimlessly with the fluid, ranging from small cylinders to large heterogeneous structures (García Ladona *et al.* 2016). However, except for small units that simply float on the surface of the sea, all drifters still have a buoy from which a line hangs with a drag element. The fundamental principle for following the current has not changed over time: the dragging element offers substantial resistance to the movement of the fluid, so the entire structure (or drifter) moves with the same speed as the fluid that surrounds the drogue.

Since 1988, standards for surface drifters have been established, so drogues meet resistance-to-flow requirements that allow trajectories to be compared in different places and in different meteorological and oceanographic conditions (WOCE 1988) (Figure 1). In order to transmit its position, all drifters require a floating element on the sea surface where the transmitter is placed. This is because electromagnetic waves attenuate very quickly in seawater: for example, a radio wave with a frequency of 800 MHz would not penetrate even a centimetre of water.

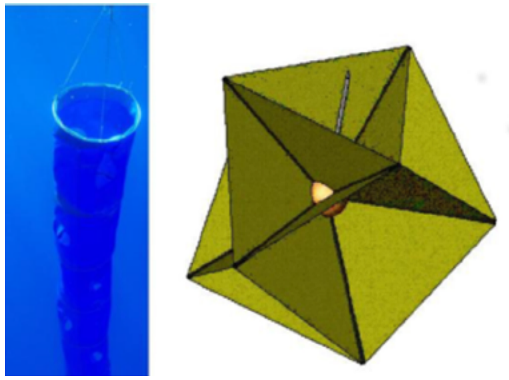

Figure 1. Drag elements in drifters: the left photo shows a hanging sock-shaped drogue that is typical of the WOCE programme (1988), and the right photo shows a spherical-shaped drogue with a similar performance (Gasser *et al.* 2001).

Recording of successive surface buoy positions has also significantly improved, especially since 2000 when the United States government ended restrictions on the accuracy of GPS data. Additionally, these drifters may now incorporate various sensors thanks to advances in energy autonomy and can efficiently transmit position data and observed variables with the desired frequency in real time through satellite systems such as Argos, Iridium and Globalstar. All of these allow precise monitoring of the trajectory and transforma-

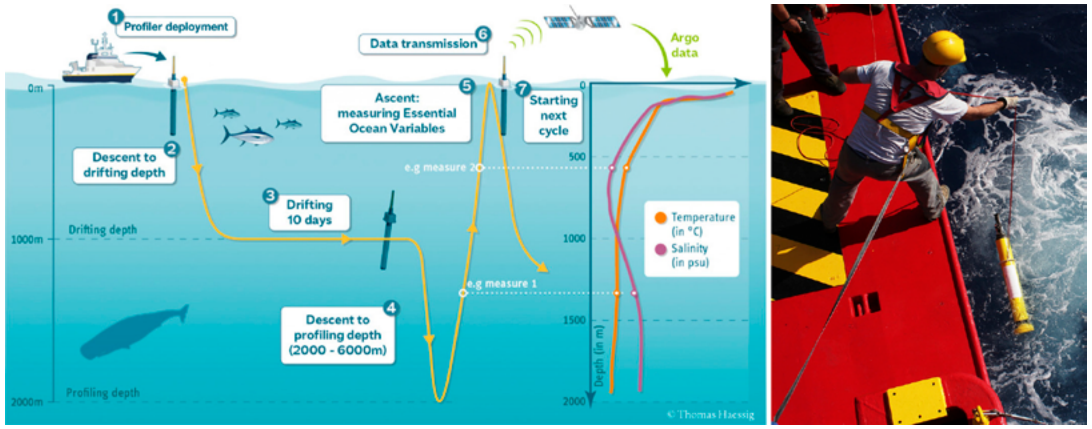

Figure 2. Characteristic cycle in the water column of an Argo programme profiler (left). Photo of an Argo profiler being launched from an oceanographic ship (right).

tions of water masses, with spatial accuracies of a few metres and at time intervals that can range from minutes to days.

Another very significant advance in our understanding of the movement and evolution of water parcels has been achieved with the international Argo programme, which began with the millennium. This programme consists of floats or profilers that drift at a certain depth and have the ability to perform vertical movements in the water with a previously established frequency (Figure 2). During these vertical movements, the profiler's sensors collect information on the vertical distribution of the properties of the water column (pressure, temperature and conductivity as standard). When the profilers reach the sea surface they stay there long enough (minutes to hours) to transmit their position and the data recorded during their vertical cycle.

The Argo programme currently has about 4,000 profilers drifting across the oceans, providing very valuable information on ocean currents and the structure of the water column.

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6.8. Autonomous platforms and their applications in oceanography

Pablo Rodríguez, Núria Pujol, Jordi Sorribas

Marine sciences and ocean observation are key to achieving a sustainable future. However, the systematic study of the marine environment is subject to strong constraints that limit its development, including the extent and accessibility of some study areas, weather, time and space scales and high operating costs.

In the last two decades, great efforts have been made to achieve a multiscale temporal and spatial vision of the sea, but this work has only just begun. The number of measured parameters and the temporal and spatial sampling frequency must be increased, and they must be made synoptic along multiple scales. Important advances in the manufacture of sensors and the gradual automation of some sampling platforms (smart buoys, drifters, gliders and autonomous surface and submarine vehicles) mark the way towards this goal, and these resources are being used increasingly in marine research (Di Caccio and Troisi 2021).

The current state of the technology

The use of large platforms (oceanographic vessels) is strongly limited by economic factors (operating costs), geographical limitations (access to remote or difficult-to-access areas) and environmental and temporal factors (vessels can only be in one place at a time and for a limited period). Despite these inconveniences and limitations, oceanographic vessels are, and will continue to be, essential for studying the oceans, and in particular for deploying and maintaining autonomous or non-autonomous instruments and sensors. Collaborative platforms such as the Ocean Facilities Exchange Group have been developed to rationalize the use of these instruments as far as possible, minimizing unnecessary movements of large platforms and thus saving money and energy.

Platforms with the capability to operate autonomously offer greater flexibility and rationalization in the deployment of sensors. They also allow the development of new operational methods such as multi-platform deployment with collaborative sampling and adaptive sampling, and can act as effort multipliers when deployed from traditional platforms. The ultimate goal is to obtain a better view of the ocean at a reasonable cost and with a lower environmental impact.

Platforms of this type have shown spectacular progress in the last 20 years, and there are currently autonomous aerial, surface and submarine platforms with very diverse operational capacities and autonomies of up to weeks or months. They were pioneered by offshore companies owing to the significant reduction in operating costs that they offered.

These platforms offer a wide variety of work capabilities related to payload and autonomy. They can house a wide range of sensors in different operational conditions and complement each other to offer a complete vision of the environment (Figure 1). They can carry out missions in a hurricane, monitor ocean currents on a global scale (Argo buoys) and constantly monitor environmental disasters like the Deepwater Horizon accident over a period of months. Some platforms, such as those forming part of the Ocean Observatories Initiative, can communicate with marine observatories,

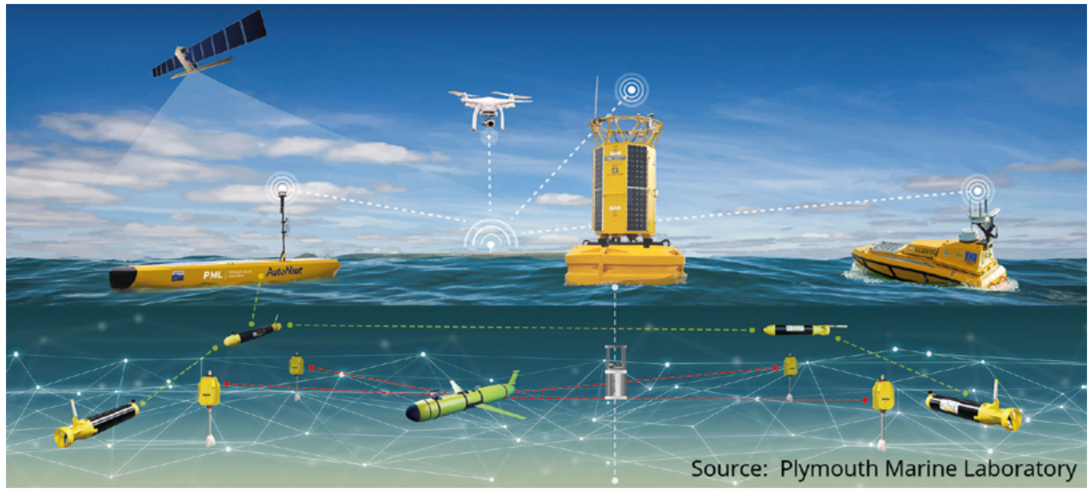

Figure 1. Autonomous observation system. Plymouth Marine Laboratory.

and their missions can be adapted according to the researchers' needs.

Future challenges

Despite the advantages of autonomous platforms, there is still a long way to go. Some of the main challenges for these technologies are described below:

Autonomy. One of the main limiting factors of autonomous platforms is their autonomy, because they are almost all battery-powered. Despite considerable advances in battery size and power, the energy density of batteries still has much room for improvement. Natural energy sources such as waves, solar radiation and wind are therefore an essential complementary power source for long-term missions.

Sensor miniaturization. Great advances have been made in the miniaturization and integration of sensors for measuring physico-chemical, optical and acoustic parameters. Temperature, conductivity, pH and oxygen sensors are now very common, but more progress needs to be made in their miniaturization to achieve a comprehensive, multiscale monitoring of the marine environment.

Data transmission. Data transmission has two important and interrelated limiting factors: the bandwidth of the channel used and the energy consumption. In autonomous vehicles it is important to control the power consumption of each element, so data transmission has to be as efficient as possible. In addition, transmission latency can also be a critical factor in some areas or scenarios, such as those related to environmental monitoring and prevention of natural disasters.

Artificial intelligence. The incorporation of new artificial intelligence processes involves exceptional challenges and opportunities. The possibility of having highly autonomous platforms capable of adapting their missions according to environmental factors or mission requirements opens up a wide range of new possibilities, such as monitoring protected spaces and studying highly dynamic phenomena.

Figure 2. Girona500 AUV model at the facilities of the Unitat de Tecnologia Marina in Barcelona.

Autonomous platforms have great potential for development in marine science, as evidenced by the firm commitment of prestigious marine research institutions to these technologies (Lindstrom *et al.* 2020). In the medium and long term, the incorporation of new technologies and methodologies in marine research will increase the resolution of small-scale studies and improve the coordination of platforms in large-scale studies (Whitt *et al.* 2020).

The Unitat de Tecnologia Marina (UTM) of the Institut de Ciències del Mar started moving in this direction some time ago and currently offers two coastal autonomous underwater vehicles and one shallow one to the marine science community (Figure 2). We feel that this field will develop greatly in the near future to offer many applications at a national level within the CSIC.

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6.9. Oceanographic cruise data management for accessible information

Susana Diez, Jordi Sorribas

During research cruises on oceanographic vessels, a large amount of data of different types are acquired, covering all study areas and characterizing and providing information on the sea surface, the water column, the seabed and the sub-seabed. These data are very valuable not only as a source of oceanographic research but also because it is difficult and expensive to acquire them in the complex marine environment. It is therefore essential to make this information accessible and reusable.

Infrastructure for data management

The management of data from oceanographic cruises requires a long-lasting infrastructure supported constantly by technical staff, so it cannot be dependent on research projects. The final objective of this infrastructure is to provide access to information related to the data acquired on cruises carried out on oceanographic vessels and to the maximum possible amount of data in an open and interoperable way, following the FAIR principles (Findable, Accessible, Interoperable and Reusable) (Wilkinson *et al.* 2016, Galiana *et al.* 2022).

A basic element of an oceanographic survey data infrastructure is the use of metadata to describe in detail the nature of the data and provide information about their acquisition: who acquired them, how, where, when, who is keeping them, etc. The metadata facilitate the indexing and searching of data sets through catalogues (Figure 1), a fundamental component of a spatial data infrastructure. The Cruise Summary Report and the Common Data Index are the metadata files of the cruises and the acquired data, respectively, and they follow the

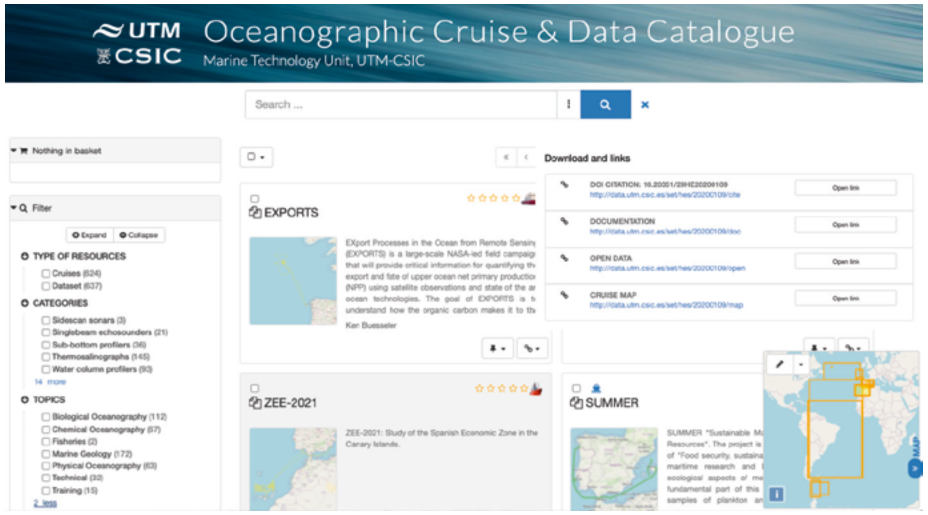

Figure 1. Oceanographic Cruise and Data Catalogue, Marine Technology Unit Data Centre, http://data.utm.csic.es

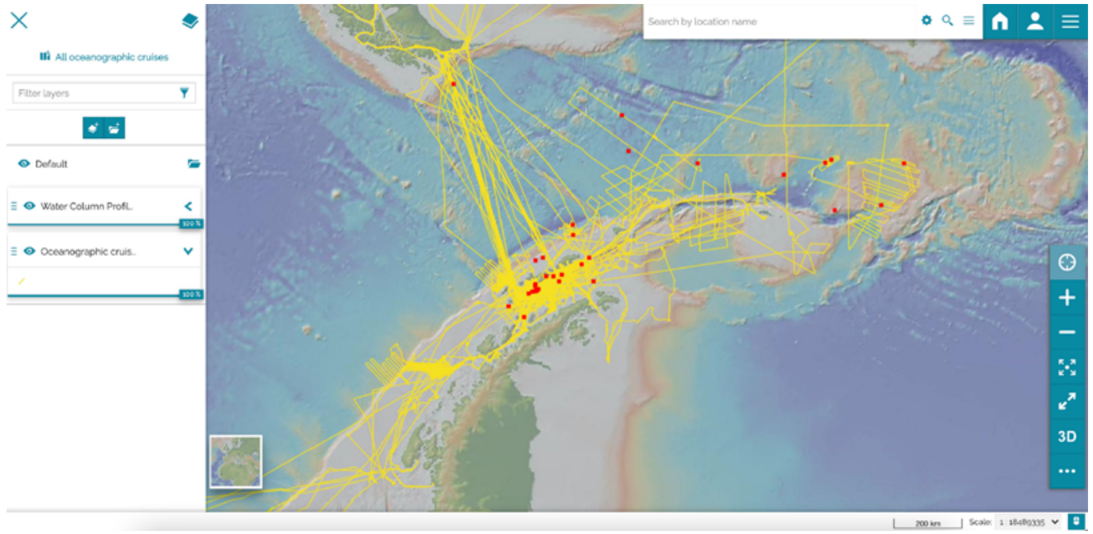

Figure 2. Geoportal of the UTM Data Centre, http://data.utm.csic.es/geoportal

standards of the European SeaDataNet infrastructure of marine data (Pecci *et al.* 2020) and are INSPIRE-compliant.

Another key element that allows spatial data and services such as the Web Map Service, the Web Feature Service and the Web Coverage Service to be discovered, visualized and accessed is the Geoportal (Figure 2), a web portal that uses map browsing. Users can add their own data and create their own maps. The query and search results are ideally linked to the metadata catalogue.

The development of tools and applications for visualization, quality control and data transformation to standard formats is equally important, so that interoperable data are available.

The custody of all data and access to open data are performed through data repositories. The data from oceanographic cruises acquired in the framework of projects financed by the National Research Plan are restricted by an embargo period of two years after the end of the project with which the cruise is associated (Resolution Call "R+D+i Projects" 2020). After this period, the data become open and are accessible through data facilities such as the Data Centre of the Unitat de Tecnologia Marina (UTM).

In order to offer an efficient way to facilitate citation of the data sets of an oceanographic cruise, the most widespread form that is being imposed in this field is the use of the digital object identifier (DOI) system (The DOI Handbook): an identifier and a permanent URL, which allows a resource to be located without changing its address over time, even if it is relocated to a different application or domain. The UTM generates DOIs for the data sets of each oceanographic cruise through the CSIC's membership in DataCite, one of the main registration agencies.

In order to also disseminate the data and metadata of oceanographic cruises at an international level, collaboration and participation in various infrastructures is necessary. SeaDataNet is a standardized and distributed pan-European infrastructure for managing data sets collected by oceanographic fleets and automatic observing systems. SeaDataNet connects data centres (such as the UTM's) from more than 30 countries, with the aim of preserving and being able to reuse marine data from different spheres.

Challenges in the data management of oceanographic cruises

The challenges in the management of oceanographic vessel data include, first, the progressive incorporation of all historical data, which involves a significant effort of harmonization and quality control and the generation or revision of metadata. Second, the constant contribution of new data and metadata from new oceanographic surveys is essential. Third, according to the European regulations on open data and reuse of public sector information (EU Directive 2019/1024), access must be given to the maximum possible amount of data, including unrestricted data and data or derivative products that the scientific community voluntarily decides to publish openly.

To achieve these challenges, it is necessary to join forces with related organizations so that data management becomes an essential resource providing Spanish, European and international oceanography with accessible and useful information for learning about the oceans.

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6.10. Sensing the seafloor with fibre-optic telecommunication cables

Arantza Ugalde

Studying earthquakes is key to answering fundamental questions about the dynamics and physical properties of the earth's interior. Although earthquakes can occur at any time and place on the planet, observations have shown that most of their energy is released at the boundaries between tectonic plates. For the most part, these seismic belts are located under the ocean floor, which covers 70% of the earth's surface. However, the seismological networks that detect earthquakes are located mainly on land, so it is difficult to use their records to obtain a complete image of the interior of the planet. Marine geophysical research is carried out with large research ships tasked with deploying temporary ocean floor seismometers which, together with a limited number of permanent underwater observatories, have led to significant discoveries under the ocean. However, this type of instrumentation is difficult and expensive to install and maintain, so we are still a long way from having submarine seismic networks that are comparable in number, density and characteristics to those existing on land.

Telecommunication cables as sensors

The deep sea is home to an extensive communications network that connects countries and continents through submarine cables that are more than a million kilometres long and are continually increasing (Figure 1). The cables consist of a core of optical fibres that transmit light signals and are covered with a series of layers that waterproof and protect them from the environmental conditions. A new technology called distributed acoustic sensing (DAS) converts each cable into tens of thousands of seismic sensors (Zhan 2020). To do this, it is only necessary to connect an interrogator unit at the end of a single dark fibre and emit pulses of laser light through it.

Optical fibres contain inhomogenities as a result of the glass cooling process during their manufacture. When a beam of light is transmitted through a fibre, these inhomogenities cause the scattering of small fractions of light that are reflected back towards the interrogator unit, which detects and identifies them as reference points. When the fibre is deformed as a result of the arrival of seismic waves, the reference points also change their position (about one nanometer for each metre of cable), thus modifying the arrival time of the backscattered light to the interrogator unit. It is thus possible to measure the relative deformations along many kilometres of fibre-optic cable very precisely.

An underwater revolution

DAS technology has enormous potential for monitoring remote or inaccessible underwater regions. Compared with conventional underwater seismic networks, it has the advantage of providing measurements with unprecedented spatial resolution (of the order of a few metres over several tens of kilometres). It is a remote sensing technology and is therefore non-intrusive. It is also very economical because it uses existing telecommunications infrastructure.

In 2019, six years after the first descriptions of the potential use of DAS in seismic monitoring, an earthquake of magnitude 8.2 was detected for the first time with this technology.

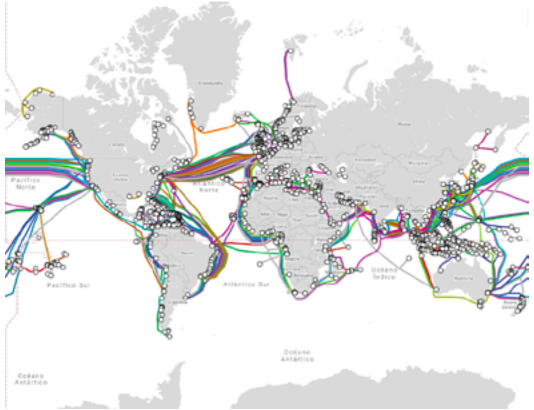

Figure 1. Map of the main submarine telecommunication cable systems and land stations (white circles). Source: TeleGeography (https://www.submarinecablemap.com/, accessed on 02/06/21).

It occurred in the Fiji islands, more than 16,000 km away from the submarine cable located off the coast of Belgium (Williams *et al.* 2019). In the same year, a 1.9 magnitude earthquake was observed 100 km from another cable located in southeastern France (Sladen *et al.* 2019). Since then, seismic observations by submarine cables have increased continually (Figure 2).

In addition to earthquakes, DAS observations from submarine cables show a diverse collection of signals, including ships, large marine mammals, tides and currents, thus opening up this technology to a wide range of possibilities.

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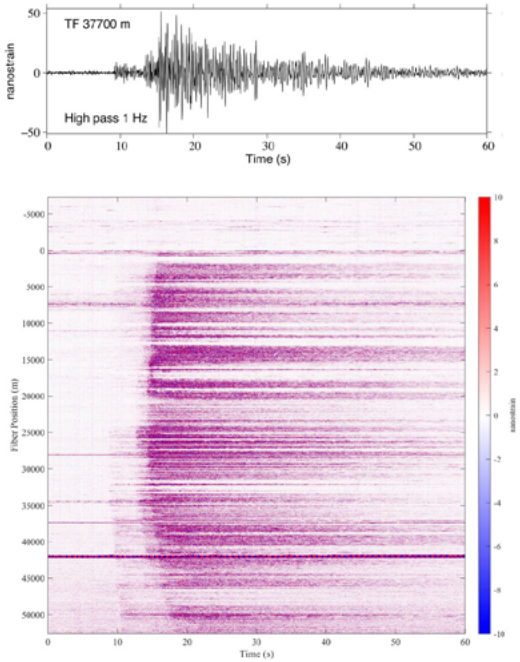

Figure 2. One minute of recording with DAS of the 3.1 magnitude earthquake that occurred in the Canary Islands on 27 July 2020. Above: observations at 37.7 km from the cable. Bottom: observations along the 60 km of optical fibre. The fibre's 0 position marks the cable's entry into the ocean. Source: Ugalde *et al.* (2021).

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6.11. Jellyfish prevention and post-sting tools based on R&D&I strategies

Ainara Ballesteros, Macarena Marambio, Josep-Maria Gili

Cnidarians, an animal group to which jellyfish belong, have distinctive stinging cells called cnidocytes. These cells are distributed throughout the epidermis and are more abundant in the tentacles. Their functions are mainly related to prey capture and defence against predators, but they also allow them to fix themselves to the substrate and to move. Within the cnidocyte is the nematocyst, the capsule occupying most of the cell where the venom is stored, together with a coiled tubule, sometimes including spines (Figure 1). In response to a chemical and/or mechanical stimuli detected by a hair-like trigger called a cnidocil, the operculum opens, initiating the discharge of venom, one of the fastest exocytosis processes in the animal kingdom (Figure 2).

Cnidocytes are present throughout the life cycle of jellyfish, from small planulae to adult individuals. Cnidocytes are differentiated by their morphology, the characteristics of the tubule and the pattern of their spines. While some types are very common across species, others are characteristic of certain groups of cnidarians.

Although there are no jellyfish species with a lethal venom in the Mediterranean Sea, their massive and continued presence on the coasts generates negative socio-economic and environmental impacts. The stings of the most common jellyfish species in the Mediterranean Sea,

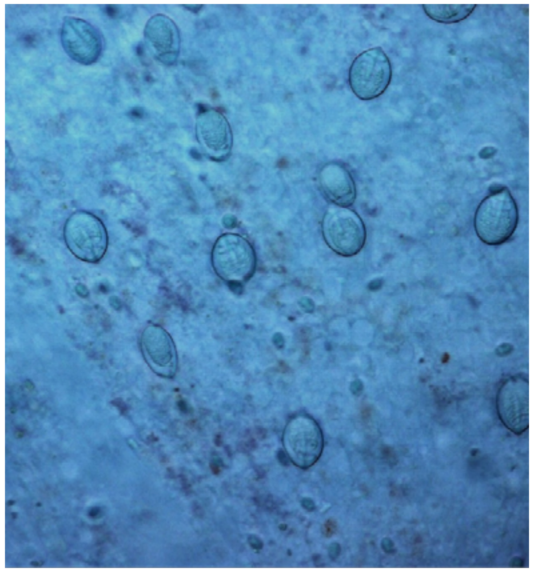

Figure 1. Nematocysts identified in the jellyfish *Pelagia noctiluca*, considered the most widespread jellyfish in the Mediterranean Sea. Note the coiled tubule inside the capsule along with the venom.

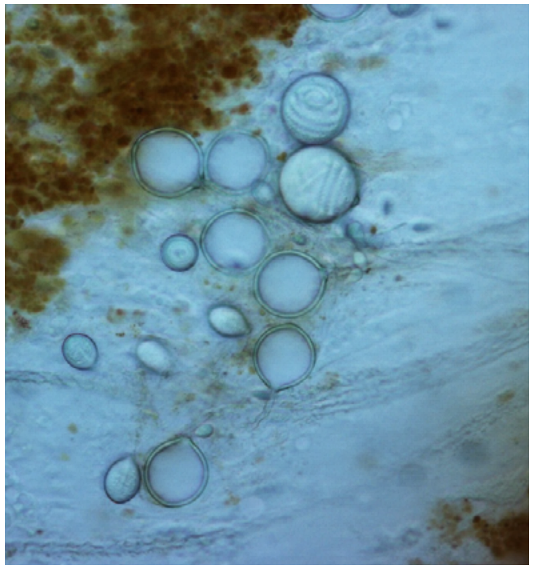

Figure 2. *Pelagia noctiluca* nematocysts discharged after activation. Note the empty capsule in the discharged nematocysts due to the discharge of the tubule, which serves as a conduit for inoculation of the venom.

Pelagia noctiluca and *Rhizostoma pulmo*, cause local reactions such as burning, oedema, swelling and dermatitis, but systemic symptoms are rare. However, the occasional presence of *Physalia physalis* can cause serious health problems due to its high toxicity. During the bathing season, jellyfish stings account for the highest number of cases dealt with by lifeguard services in Spain.

First-aid protocols against jellyfish stings

The presence of jellyfish is increasingly common in many areas of the Mediterranean. Incidents involving them on beaches have increased, focusing the attention of the scientific community, governments and society to seek solutions that minimize the problem and avoid social alarm. Joint research projects have been initiated between marine biologists, oceanographers and health workers, providing society with tools for mitigating the problem such as preventive measures at the beach and first-aid protocols (Marambio *et al.* 2021).

Following accidental contact with jellyfish, residual tissue or cnidocytes may adhere to the skin. First-aid protocols therefore focus on the application of rinse solutions to safely remove the remains without causing a second poisoning. This step of the first-aid protocols has achieved a consensus among the scientific community, but there is no consensus about which substance to use for washing the stung area. While some researchers suggest the universal use of vinegar (Doyle *et al.* 2017), others consider it to be inefficient because it activates the cnidocytes in some species (Ballesteros *et al.* 2021). Systematic reviews recommend the re-evaluation of the substances used and encourage the search for new compounds that can be used universally.

Synergy between public research centres and private companies

Many of the proposals for solving the impact of jellyfish stings lack a thorough knowledge of the biology of the species and their anatomical and physiological characteristics. The line of jellyfish research at the Institut de Ciències del Mar (ICM-CSIC), which has been operative for more than 20 years, has allowed us to obtain sound multidisciplinary knowledge of the species of jellyfish and their cnidocytes, promoting a research, development and innovation strategy (R&D&I). Companies in the pharmaceutical and cosmetic industry are therefore keen to carry out industrial projects with the ICM-CSIC. Industrial doctorate projects have recently facilitated collaboration between companies and ICM-CSIC in order to search for new preventive and post-sting tools to mitigate the effects of jellyfish stings on beach users. The experience of recent years has shown that basic research on the biology, physiology and ecology of species is a fundamental value for demonstrating to the business community the potential for carrying out applied and industrial projects.

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6.12. The emergence of iEcology and conservation culturomics for the sustainable development of our oceans

Valerio Sbragaglia, Lucía Espasandín Soneira, Jeroen Steenbeek, Karen Soacha Godoy, Jaume Piera, Marta Coll

Our oceans are essential for life on Earth, but they are seriously threatened by the cumulative effects of anthropogenic pressures, including habitat loss, climate change, invasive alien species, pollution and unsustainable harvesting (IPBES 2019). The unprecedented ongoing marine biodiversity crisis may have profound effects on ecosystem services and human well-being.

Despite recent efforts, many aspects of this crisis remain unsolved for various reasons, including (1) the lack of resources for collecting the necessary ecological and socio-economic information; (2) the constrained monitoring activities across time and space, and (3) the fact that many impacts occur faster than our capacity to track and manage them. Furthermore, exploring the human-dimension of the biodiversity crisis is especially challenging because social science is still not sufficiently integrated into marine research. As a result, we frequently lack the necessary information to guide decision-makers at relevant scales. There is an urgent need to overcome these monitoring and knowledge gaps by taking advantage of effective research methods and data sources.

A new research approach

Over the past decade, the internet, and social media in particular, have become important repositories of human culture, knowledge and social interaction in digital formats and in unprecedented volumes. This has fostered the emergence of two new research approaches: iEcology (Jarić *et al.* 2020a) and conservation culturomics (Ladle *et al.* 2016). Although both approaches perform quantitative analyses of large volumes of digital data, iEcology aims to characterize ecological patterns and processes (e.g. species occurrences and distributional range shifts; Jarić *et al.* 2020a) from digital data generated for other purposes, whereas conservation culturomics aims to characterize and understand contemporary problems in conservation from the perspective of human-nature interactions (e.g. attitudes of stakeholders and human behaviour in the context of resource exploitation; Ladle *et al.* 2016). The expansion of iEcology and conservation culturomics from the terrestrial to the aquatic realms is expected to play an important role in informing and analysing many conservation actions such as management of protected areas, sustainable fisheries, biological invasions and the assessment of ecosystem status and anthropogenic and social impacts (Figure 1; Jarić *et al.* 2020b).

Integration of iEcology and conservation culturomics with citizen science

One of the most interesting and challenging aspects of iEcology and conservation culturomics for the sustainable development of our oceans is the integration with state-of-the-art citizen science observatories (Figure 2). There are two major aspects that make this integra-

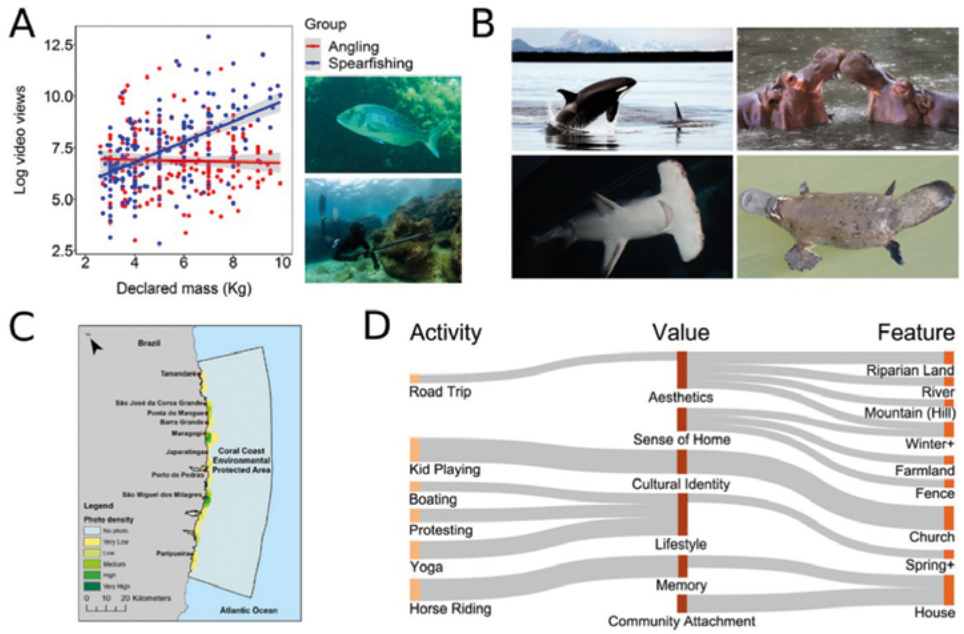

Figure 1. Examples of aquatic culturomics and iEcology studies according to Jarić *et al.* (2020b). A, social engagement of marine recreational anglers and spearfishers targeting common dentex (*Dentex dentex*), an iconic species for Mediterranean fisheries, based on videos posted on YouTube. Upper photo, common dentex; lower photo, spearfisher. B, potential aquatic flagship species identified on the basis of their popularity (relative internet search frequency); presented are top-ranked marine (killer whale, *Orcinus orca*, and great hammerhead, *Sphyrna mokarran*) and freshwater species (hippopotamus, *Hippopotamus amphibius*, and platypus, *Ornithorhynchus anatinus*). C, mapping of cultural ecosystem service hotspots in a marine protected area, based on social media photographs. D, conceptual landscape perception map, based on statistical relationships between activities, values, and features coded from landscape images and captions on Instagram, from the proposed headpond area of the now-approved Site C dam, Peace River, British Columbia, Canada. See Jarić *et al.* (2020b) for original studies presented in this figure. Source: https://doi.org/10.1371/journal.pbio.3000935.g001.

tion pressing. First, citizen science can provide complementary knowledge that can help to advance the understanding of marine biodiversity processes and patterns (Soacha Godoy *et al.* 2022). Second, the unprecedented and rapidly growing volumes of digital data offer great scientific potential when analysed with the help of machine learning for filtering and interpreting digital content such as text, pictures, and videos (Toivonen *et al.* 2019).

A fundamental step for machine learning to work properly is producing learning libraries with human supervision. This can be a challenging task, especially in the context of big data coming from different countries. In this context, standardization, interoperability and collaborative work within citizen science observatories can be an effective solution to foster validation processes. Technological services that help increase the availability of citizen science data under the FAIR (findability, accessibility, interoperability and reusability) principles (Galiana *et al.* 2022) are part of the strategy that the European Open Science Cloud is promoting (https://eosc-portal.eu/). Generating FAIR data also relies on a proper engagement and recognition of the community of volunteers and experts that create and validate the data. For example, species identification is one of the areas where these approaches can be applied. The collective work of a large number of volunteers can result in accurate classifications and consequently contribute to the development of effective training libraries for operationalization of machine learning algorithms in the context of iEcology and conservation culturomics. In addition, as there are no prescribed standards for internet content moderation and quality control, open peer-reviewed data repositories, stakeholder consultation, citizen science and machine learning algorithms are complementary approaches to peer-reviewing online content. This includes

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Productive ocean
Predictable ocean
Safe ocean
Accessible ocean
Inspiring and engaging ocean
Indexes

From notebook to cloud data
Technical support to science
Geological collections
Biological Reference Collections
Gender equality in marine research
A new generation of research vessels
Observing the evolution of a water particle
Autonomous platforms in oceanography
Oceanographic cruise data management
Sensing the seafloor with fibre-optic cables
Jellyfish prevention and post-sting tools
The emergence of iEcology
Citizen science and participatory monitoring systems

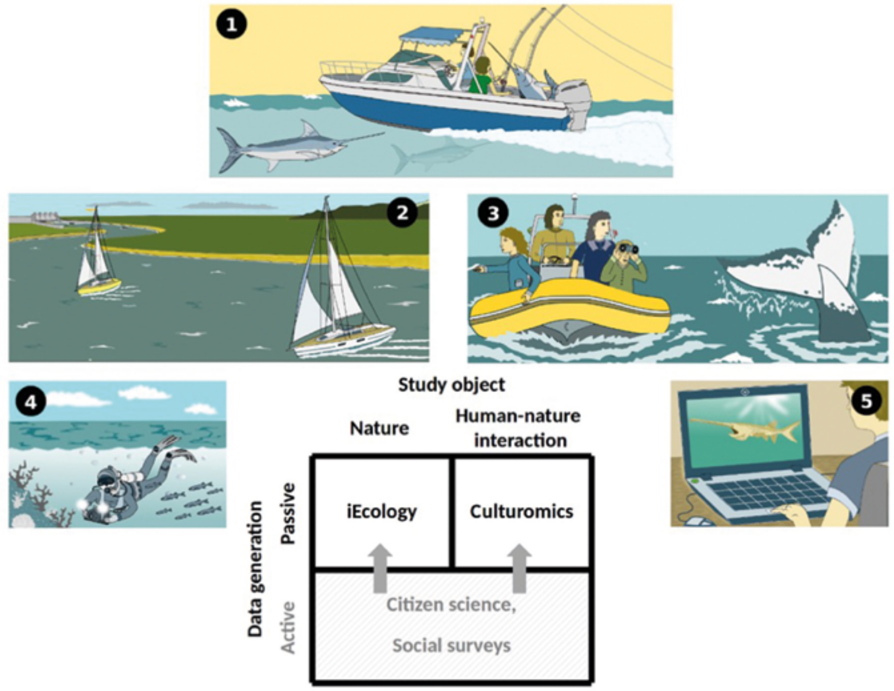

Figure 2. A conceptual diagram with key differences between culturomics, iEcology and other related approaches such as citizen science and social surveys according to Jarić *et al.* (2020b). Differences are based on the object of study (human-nature interactions or nature itself) and the type of data generation (passive or active). Data sets generated by citizen science, social surveys and other approaches can also represent data sources for iEcology and culturomics, as indicated by arrows. The drawings illustrate some applications of culturomics and iEcology for aquatic research: 1, fisheries management; 2, social impact assessment; 3, detection, mapping and monitoring of threatened, rare and alien species; 4, ecosystem status and anthropogenic impacts; and 5, identification of aquatic flagship and umbrella species. Source: https://doi.org/10.1371/journal.pbio.3000935.s001.

validating, interpreting, quantifying, fact checking and bias correcting of media posts in order to turn raw internet data into usable quantified information for scientific uptake.

Conservation culturomics and iEcology are expected to undergo massive development in the next decade and play a major role in guiding the sustainable development of our oceans. The functional integration with digital citizen science observatories can boost and reinforce this process.

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6.13. The contribution of citizen science and participatory monitoring systems to ocean knowledge and conservation

Karen Soacha Godoy, Jaume Piera, Sonia Liñán, Carlos Rodero, Xavier Salvador, Raúl Bardají, Valerio Sbragaglia

The ocean and its biodiversity shape the characteristics of the Earth. The ocean dictates our climate, represents a large part of our food supply, plays an essential role in the global economy and supports a great diversity of life and ecosystems. The ocean and humans are deeply interconnected. However, our knowledge of this important ecosystem is relatively limited: it is estimated that less than 5% of it has been explored, and, as a result, there could be about one million species unknown to science (Ocean Literacy Network 2020). There is an urgent need to increase our knowledge of the oceans at a faster rate. Citizen science and participatory monitoring systems are part of the critical strategies for reducing these knowledge gaps.

Citizen science is a growing practice in which scientists and citizens actively collaborate to produce new knowledge for science and society (Vohland *et al.* 2021), but it is not a new practice. Historically, fishers and sailors have contributed their observations and knowledge to the study of marine life and the understanding of the ocean. The collaborative production of knowledge between scientists and volunteers in the ocean, including coastal beaches and estuaries, is known today as marine citizen science (MCS).

Marine citizen science: context and contribution

Thousands of volunteers have been involved in a wide range of marine research, such as collecting observational data on marine species and monitoring marine debris and environmental variables such as water turbidity, sediments and other essential variables for monitoring climate change. MCS is also a powerful tool for monitoring the arrival and encroachment of invasive non-native species. It is estimated that 500 MCS projects are currently underway in Europe, with exponential growth since 1990, and this trend is reflected globally (Garcia-Soto *et al.* 2021). In most MCS projects, volunteers are exclusively involved in data collection (Garcia-Soto *et al.* 2021). More collaborative approaches in which citizens participate in the whole research process are less common but extremely necessary for generate a transformative change both in the way of building knowledge and in its ability to impact socio-ecosystems.

MCS projects vary from days to decades and focus mainly on coastal ocean environments, closely followed by easily accessible coastal regions. The most popular methods for collecting data are field surveys and reporting of opportunistic sightings. Novel methods are also developed, such as ocean temperatures recorded from divers' computers and surfboard fins with sensors that collect real-time ocean parameters (Earp *et al.* 2020). Technological innovation has also made it possible to expand the spectrum of participation, for example, with do-it-yourself sensors such as KdUINO, which measures water transparency, or through the *Patí Científic* platform, which uses the instrumentation of recreational boats to capture oceanographic variables. Virtual participation has also made

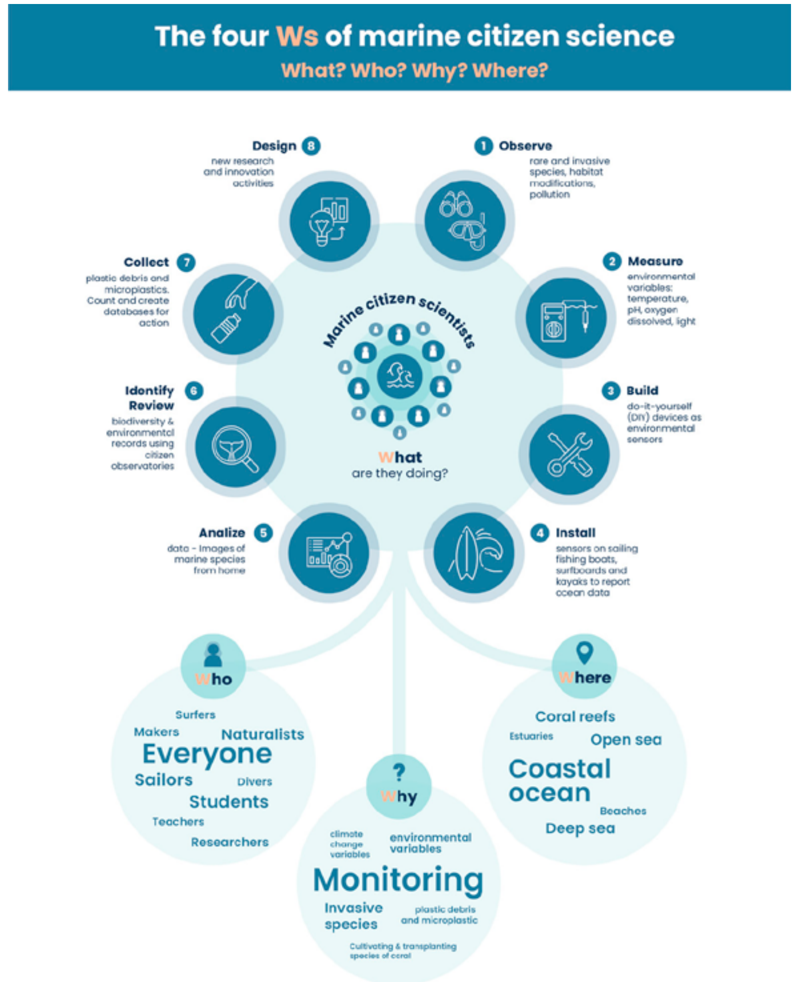

Figure 1. The four Ws of marine citizen science: What? Who? Why? Where? The spectrum of participation in marine citizen science (MCS) is wide. More and more enthusiasts and researchers collaborate by collecting data, analyzing information, building monitoring devices, and even designing investigations. The 4ws of MCS is a panoramic look at the diversity of participant profiles, activities that are being carried out, types of projects and ecosystems in which MCS has been contributing to the knowledge of the ocean.

its way into MCS. Volunteers from around the world participate "virtually" from the comfort of their homes, analysing over two million images of the seafloor to investigate the distribution of commercially important marine species. Other approaches such as iEcology and Culturomics also use data accumulated in digital sources generated passively or unintentionally by citizens to quantify patterns and processes in the natural world (Sbragaglia *et al.* 2022).

MCS has also been contributing to scientific publications. Earp *et al.* (2020) identified that 44 MCS projects had contributed data to at least 1483 peer-reviewed journal articles. Other significant contributions to the documentation of marine life are biodiversity guides authored by citizen scientists; some examples are the Seasearch guide of sea squirts and sponges of Britain and Ireland and the recent Barcelona Participatory Marine Guide. Another significant contribution by MCS includes enhanced marine policy and environmental stewardship. Marine regulation often requires evidence supported by large databases that citizen science can provide cost-efficiently. For example, in the UK, the Seasearch data set that extends back to 1984 has contributed to the designation of 38 marine conservation zones and several other marine protected areas (Earp *et al.* 2020). Climate change has been another area in which MCS has contributed. The Marine Biodiversity and Climate Change (MarClim) project continuously provides data to highlight changes in the geographical distribution of marine species caused by climate change and offers advice for policy-making.

Marine citizen science: challenges and opportunities

Data quality and long-term engagement of participants are among the most common challenges facing MCS projects. Despite evidence that the quality of citizen science data is comparable to that collected by scientists, it is not yet fully recognized by the scientific community (Martin *et al.* 2016). Many factors also affect participant engagement, especially because marine systems pose their own unique challenges: greater inaccessibility makes them less easy to monitor than land-based habitats, and the logistics can require boats, diving gear, specific equipment and previous skills in the case of diving for example.

Overcoming these challenges involves designing activities for the wider public that eliminate as many barriers as possible, such as observation in accessible coastal areas focusing on mammalian, avian or seashore species, which can be identified above water. Also, the strategies implemented should consider social factors, such as the networks of participants (i.e. family and friends) to increase long-term involvement (Martin *et al.* 2016). Regarding data quality, it is important to increase the use of standards in the citizen science community and to promote interoperability between platforms. It is also necessary to strengthen the infrastructure to facilitate the publication of open data following the principles of FAIR data (findability, accessibility, interoperability and reusability). Strengthening the technological facilities that support citizen science, known as citizen observatories, is also necessary. These facilities allow biodiversity and environmental data to be gathered, stored and made available in an open and interoperable space. Another way to decrease knowledge gaps and increase engagement is to strengthen the citizen observatory mechanisms for collaborative validation of observations.

MCS has been shown to have great potential for reducing ocean knowledge gaps and contributing to the conservation and management of marine ecosystems. Its ability to generate information on multiple spatio-temporal scales, to actively involve a wide range of stakeholders and to increase ocean literacy makes it a pillar for achieving a sustainable ocean.

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Photo: Blanca Figuerola

7. Inspiring and engaging ocean

Pedro Cermeño, Vanessa Balagué, Carine Simon

The word ocean comes from Oceanus (Greek: *Ōkeanós*), the elder of the Titans in classical Greek mythology, believed to be the divine personification of a gigantic river that encircled the world. The history of humankind is full of mythological water deities, gods of the ocean and the rivers created by ancient civilizations to represent the strengths of nature and human facets. For millennia, the oceans have been a powerful source of inspiration for philosophers, artists and merchants, from the Greeks and Romans to the fearless sailors of the Middle Ages. Today, the oceans remain a source of inspiration and curiosity fuelled by the tremendous scientific knowledge and social awareness acquired in recent times.

In this chapter "Inspiring and engaging ocean", the authors delve into our logical but also artistic and spiritual relationship with the oceans, how we must interact with the oceans to be part of them rather than their owners, how to transmit wisdom and passion for the oceans and how to protect them. Finally, looking into the future, the authors claim that we need the oceans much more than they need us.

The 2020s, the United Nations Decade of Ocean Science for Sustainable Development, should be the starting point for driving a change in the way humans deal with the oceans. We must realize that many of the ocean's living and non-living resources are exhaustible, that the oceans represent a crucial sink for atmospheric carbon dioxide and other greenhouse gases, and that they act as a global transporter of heat from the equator towards the poles, helping to make Earth a habitable planet.

The history of the oceans is the history of life. Like Gaia, the mother of Oceanus to the ancient Greeks, we must learn to live in harmony with the oceans. They gave us life as Gaia gave it to the oceans.

7.1. An opportunity for harmonic development with nature

Josep L. Pelegrí

January 2021 marked the beginning of the Decade of Ocean Science for Sustainable Development proclaimed by the United Nations and coordinated by the Intergovernmental Oceanographic Commission. The main objective of the Ocean Decade, which will run until the end of 2030, is to promote management of the coasts and oceans based on scientific knowledge, making healthy oceans one of the pillars for the progress of all humanity.

Under the slogan *The science we need for the ocean we want*, the Ocean Decade is based on the premise that ocean science should promote the 2030 Agenda for Sustainable Development. This will only be possible through a reflective, inclusive and transformative process that arises from scientific knowledge and incorporates the participation of government and civil organizations, with a transformative reach towards the entire international community and the planet itself.

This essay begins by recalling the main role of the oceans as architects of life on our planet and the possibilities that the ocean offers us as a source of sustainable resources. It concludes by reflecting, from a naturalistic perspective, on the principles of social justice and individual and collective evolution that underlie the concept of sustainable development.

The oceans: our largest shared common resource

The oceans regulate the life of our planet: that of every species, including humans, and of the living planet itself (Pelegrí 2021). About 97% of the water on the planet's surface, which is the basis of life, is found in the oceans. The excess of oceanic evaporation contributes 34% of the water that precipitates on the continents, therefore maintaining the life of terrestrial ecosystems.

The oceans are the main architects of the complexity and resilience of our planet. They are great repositories of solar energy and, together with the atmosphere, distribute it among different regions. They also accumulate most of the nutrients and minerals that make up the life cycle on scales ranging from seconds to millennia, and are the main regulators of greenhouse gases that determine the natural variations in our climate.

The oceans are also great planetary connectors, acting as a circulatory system analogous to that of living beings (Pelegrí 2008). They maintain a continuous process of primary production and remineralization of organic matter at a global level. It is a cycle that is restarted every year, performing an optimized homoeostatic operation that only requires solar energy (Pelegrí 2019).

The resilience of the oceans also makes them great regulators of the impact of humans on the planet, which includes both global change and climate change. By global change we understand the multiple imbalances that nature experiences from the local to the planetary scale as a result of pollution, degradation of ecosystems and overexploitation of natural resources. By anthropogenic climate change, we understand the increase in the planet's temperature caused by the emission of greenhouse gases, which results above all from the use of fossil fuels. This increase in temperature is accompanied by changes in weather patterns, rising sea levels and a greater frequency of extreme weather events.

The blue economy: maritime and sustainable

Global change and climate change are the two sides of the same coin: the planetary anthropic impact that takes its toll on the most vulnerable groups. To the inequal access to basic levels of well-being, which is very evident between different communities and regions, we now add much different capacities to develop palliative measures.

All this contrasts with the vision of the ocean as a common good. The ocean provides essential ecosystem services to the entire planet and is humanity's greatest shared wealth, the basis of what we call the blue economy (UN 2021). This economy is not only a physical space of mineral resources and logistical possibilities at the service of all people but also a new way of thinking and interacting with nature.

These enduring resources are sustainable fisheries and responsible aquaculture, renewable marine and wind energy, drinking water, marine resources of animal and plant origin, and biotechnology and genetic resources (Figure 1). They also include activities centred on the coastal and marine environment, from ecological tourism to local commerce. Along with this common heritage, there are the cultural, aesthetic and physical and emotional health benefits that a sustainable natural environment provides. All of this represents an unparalleled opportunity for countless sustainable resources to be available to all people, communities and nations.

Developing in harmony

The concept of sustainable development is often associated with the idea of "using" natural systems for the well-being of humanity. The term "sustainable" presupposes a necessary condition: the method of use must not alter the temporal stability of the system. But is this condition sufficient? Is the utilitarian perspective of the planet consistent with sustainability?

From a naturalistic point of view, the health of an organism is not possible unless it develops in harmony with its ecosystem. Therefore, applied to our relationship with the planet, the concept of "use" should give way to the concept of "being a part". This arises from the very etymological meaning of the expression "sustainable development".

The word develop comes from the French *développer*: *des-envelopper*, to unfold or unfurl. Development therefore involves internal growth, the evolution of an existing or latent potentiality.

Sustainable, on the other hand, should not carry the idea of a permanent and immutable

Figure 1. Fishing represents 17% of the protein consumed globally and more than 50% in many of the least developed countries. Azwari Nugraha, provided by the author.

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Predictable ocean
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Harmonic development with nature
Mission Starfish 2030
Ocean Decade
Committed to the marine environment
The Earth's blue heart
Ocean literacy
The sea explained through oceanographic campaigns
Observadors del Mar
Artistic rigour and scientific creativity

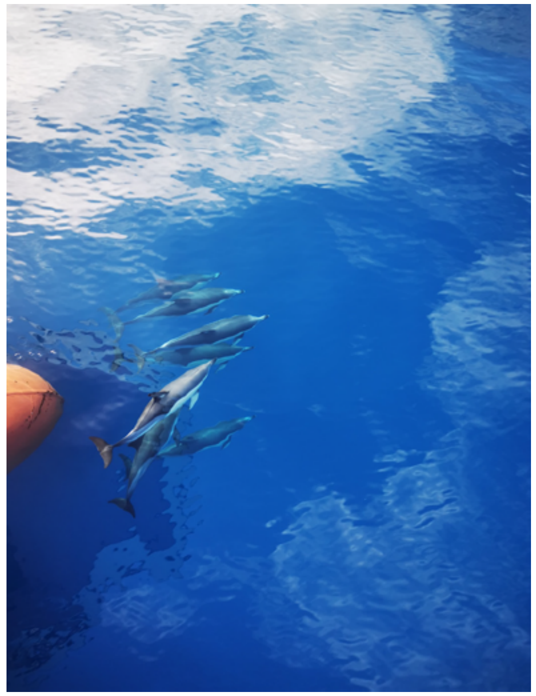

Figure 2. A group of dolphins gliding placidly in front of the R/V *Sarmiento de Gamboa* oceanographic vessel in waters off northwest Africa. Anna Olivé, provided by the author.

state but rather that of a dynamic and harmonious evolution. It is about maintaining from the base (sustainable: *subs-tenere*) a homoeostatic and resilient system, organized with a minimum of entropy, which evolves towards greater complexity.

Nature, with the oceans as its main and essential component, is the best example of sustainable development. Our challenge as a species is to be part of this harmonic planetary development. The human species can reach its maximum evolution if it is oriented towards the vital intelligence of our living planet (Pigem 2017), listening to and learning from nature, being part of it rather than owning it. Our individuality must not separate us from our communities and our communities must not separate us from the planet. Our differences do not lead us to compete. On the contrary, they complement us and contribute to the intelligence, complexity and resilience of the planet.

The sustainable development goals should not be based on a utilitarian use of nature, even if it is a sustainable use. The focus should be on being part of nature rather than possessing it (Figure 2). The development goals are an opportunity for all humanity, without exception, to achieve basic social welfare rights, which is perfectly possible with the planet's resources. Furthermore, the objectives should propel us towards a new phase in our evolution as a species, towards an individual and collective inner growth in harmony with nature.

This essay is adapted from an article published in *The Conversation* on June 7, 2021, under the title "We cannot achieve sustainable development with sick oceans" (https://theconversation.com/world-oceans-day-we-can-not-meet-sustainable-development-goals-with-a-sick-ocean-162002).

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7.2. Mission Starfish 2030: Integrative and encouraging science to restore our oceans and waters under the Horizon Europe

Sònia Sagristà, Elena Torrecilla

The UN Decade of Ocean Science for Sustainable Development is a catalyst for our oceans and will mark a turning point for marine research. It is therefore no coincidence that the main European research and innovation funding programme, the Horizon Europe, has chosen the oceans to be the focus of one of the five major scientific missions for the next seven years (2021–2027): Mission Starfish 2030: Restore our Ocean and Waters (Lamy *et al.* 2020).

The missions of the Horizon Europe research programme are a new approach to tackling the major societal challenges to which European research seeks to respond. With a multidisciplinary approach, the missions are committed to developing transformative solutions for specific problems and achieving bold, inspirational and measurable goals within a set timeframe. The European missions and the research challenges (climate, life and hazards[1]) of the Institut de Ciències del Mar (ICM) share the same integrative vision: it is the problem rather than the discipline that forms the backbone of the research (Lamy *et al.* 2020).

Mission Starfish 2030: five objectives or areas of action

Inspired by the shape of the starfish, Mission Starfish 2030 pursues five interdependent objectives: regenerating ecosystems, zero pollution, decarbonizing our oceans, revamping governance and filling the knowledge and emotional gap between citizens and our seas and rivers. The mission ultimately aims to ensure the sustainable use of the goods and services that oceans and other water bodies provide. The mission will address four challenges (an unsustainable footprint; climate change; a lack of understanding, connection and investment; and inadequate governance) by proposing five overarching objectives and 17 targets (Figure 1).

Three of the five objectives of Mission Starfish 2030 are within the realm of experimental science: regenerating ecosystems, eliminating pollution and decarbonizing our oceans. The first actions being carried out and described in the Work Programme 2021–2022 (European Commission 2021) will focus on these three objectives. These initial preparatory actions are aimed at identifying projects called "lighthouse demonstrators", which will be initiatives to guide the carrying out of a set of activities.

The two other objectives are highly social in nature and represent the main challenges for Europe and the rest of the world: to revamp the governance of our waters; and to fill the knowledge and emotional gap between citizens and our seas and rivers. To renew the governance of our waters, Mission Starfish 2030 identifies two targets: to build an integrative and participatory European system and to exercise a European leadership for effective global ocean governance. To fill the knowledge and emotional gap, the two targets proposed by the mission document are to make a marine observation system accessible to all via a digital twin of the ocean and all waters; and to make every European a citizen of our seas and waters. The question to ask ourselves is whether these four targets will be enough to achieve such ambitious objectives.

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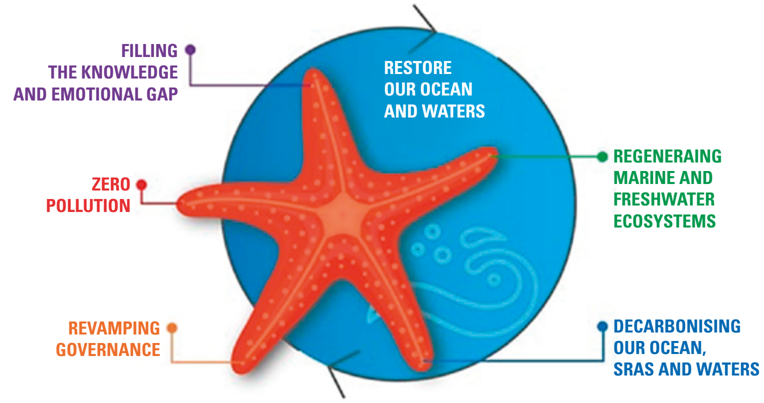

Objective		Target
Filling the knowlege and emotional gap	1	Each European is a citizen of our ocean and waters
	2	Marine and freshwater observation is stramlined and accessible to all via a digital twin of the ocean and all waters
Regenerating marine and water ecosystems	3	30 percent of EU waters are highly to fully protected
	4	Active regeneration of 20 percent of degraded habitats
	5	Renaturalise rivers and waters
	6	End overfishing
Zero pollution	7	Zero plastic litter generation
	8	Eutrophication of European seas and waters is halted
	9	Zero spill
	10	Underwater noise is regulated and reduced
Decarbonising our ocean, seas and waters	11	Climate-neutral waterborne transport
	12	Support the energy transition through renewable low-impact ocean energy
	13	Zero-carbon aquaculture
	14	A thriving blue biotech
	15	Climate-neutral blue turism
Revamping governance	16	An integrated and participatory EU system of ocean and water governance
	17	EU leadership for effectve global ocean governance

Figure 1. Five objectives and 17 targets of Mission Starfish 2030 (Lamy *et al.* 2020).

Structural change for an integrative and transformative marine science

Achieving the five objectives of Mission Starfish 2030 will require a fundamental change in our society –a structural transformation that will require an ambitious economic investment and a society that is more committed to caring for our oceans. Citizens and the economic sector will be key players in the future of European ocean science.

The three research challenges of the ICM (life, climate and hazards) are an ideal framework for contributing to the objectives set out in Mission Starfish 2030 to regenerate ecosystems, eliminate pollution and decarbonize our oceans. Likewise, the ICM's institutional values of creativity, cooperation and commitment allow us to approach collaboration with government organizations naturally and integrate citizens with our science.

Thanks to its nature and its track record, the ICM is well placed to meet the demands of carrying out excellent and transformative marine science in Europe in the coming years. However, a focus must be placed on the structural change that these demands involve. It is essential to fully consider how the science and knowledge generated by the ICM can promote a deep involvement of society in caring for our oceans, and how it can encourage ambitious investment to boost the blue economy. If in a few years' time, when the Horizon Europe and the Decade of Ocean Science for Sustainable Development come to an end, we want to be able to say that we have built the future we now envision for the oceans, it will not be enough to have generated knowledge of scientific excellence. Integrative and transformative ocean science is required. Marine research for a healthy planet must go beyond the 17 targets proposed by Mission Starfish 2030.

The greatest individual and collective challenge for all members of the ICM will be to promote a stimulating and enthusiastic marine science that involves people and generates empathy and that promotes strategic alliances and the confidence of industry. To move in this direction, in recent years the ICM has pursued a more collective governance; a greater integration between management and research; the creation of working groups with a cross-cutting impact and a clear focus on quality seals; and an organization based on specific committees for strategy, marine science culture and scientific-technical services. We must all help ensure that the marine culture and research generated by the ICM for a healthy planet plays an active role in Mission Starfish 2030.

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(1) The three research challenges of the ICM are understanding ocean and climate interactions (climate), conservation and sustainable use of marine life and ecosystems (life), and comprehension and mitigation of anthropogenic and natural hazards (hazards).

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7.3. Ocean Decade. A decade towards participatory governance of the oceans

Vanessa Sarah Salvo

Climate change, pollution, shipping, overexploitation of natural resources, habitat loss and reduction are some of the pressures affecting our blue planet. In 2016 the First Global Integrated Marine Assessment - World Ocean Assessment I (UN 2016) highlighted that urgent action on a global scale is needed to protect the world's oceans. The Intergovernmental Oceanographic Commission of UNESCO (IOC) (https://ioc.unesco.org) responded to this call by experts with the Ocean Decade proposal. The IOC is the United Nations body responsible for supporting global ocean science and services. It encourages its 150 Member States to work together to protect the health of our oceans, fostering the scientific and institutional capacity to reach global targets such as the 17 Sustainable Development Goals of UN Agenda 2030, the Paris Agreement on Climate Change (UNFCC 2015) and the Sendai Framework on Disaster Risk Reduction (UNISDIR 2015). The IOC proposal for the Ocean Decade was registered as RESOLUTION XXIX-1[(1)] in the assembly of June 2017. In December of the same year, the United Nations General Assembly proclaimed the UN Decade of Ocean Science for Sustainable Development (2021–2030) under the slogan "The Science We Need for the Ocean We Want".

The Ocean Decade is an opportunity to bring together stakeholders at a global level under an alliance for ocean science to face the degradation of marine ecosystems involving the loss of ecosystem services. This initiative aims to foster transformative actions regarding knowledge, innovation and technology through exchanges of best practices, education and capacity building for ocean sustainability. The purpose is to co-design and co-deliver actions towards global solutions to face and overcome the challenges of our oceans. Participation, collaboration and co-design are keywords for the multidisciplinary work required for transformative solutions at the local, national and regional levels.

The strategic objective is to move from the *ocean we have*, affected by anthropic impacts, to the clean and healthy *ocean we want*. This change will be achieved by means of a participatory path in the framework of the *science we need* (Figure 1), following three objectives:

1. To identify the required knowledge for sustainability.
2. To build capacity and generate comprehensive knowledge towards the understanding of the ocean.
3. To enhance the use of ocean knowledge for sustainability.

International and multidisciplinary groups of experts have supported the Ocean Decade and have identified 10 challenges concerning the *science that we need* to reach the Ocean Decade outcomes, divided into three areas:

1. Knowledge and solution challenges.
2. Essential infrastructure challenges, or the tools required to achieve the objectives.
3. Foundational challenges to guarantee inclusion and the cultural change that is needed.

These 10 Challenges may evolve and change during the decade on the basis of the stakeholders' capability to accomplish the outcomes' roadmap (Table 1).

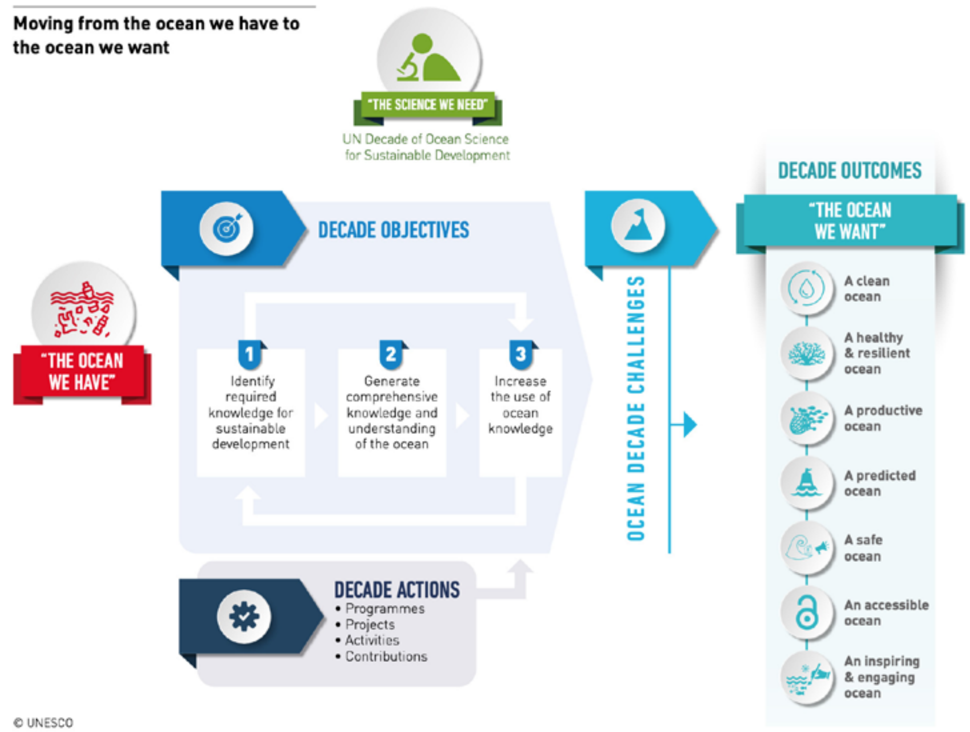

Figure 1. Ocean Science for Sustainable Development

Table 1. The seven outcomes (IOC-UNESCO 2020).

Nº	Outcomes	Description
1	A clean ocean	Where sources of pollution are identified and reduced or removed.
2	A healthy and resilient ocean	Where marine ecosystems are understood, protected, restored and managed.
3	A productive ocean	Supporting a sustainable food supply and a sustainable ocean economy.
4	A predicted ocean	Where society understands and can respond to changing ocean conditions.
5	A safe ocean	Where life and livelihoods are protected from ocean-related hazards.
6	An accessible ocean	With open and equitable access to data, information and technology and innovation.
7	An inspiring and engaging ocean	Where society understands and values the ocean in relation to human wellbeing and sustainable development.

The pathway towards the Culture of the Ocean

Participation, cooperation and science are fundamental for planning and managing actions under the objectives of the Ocean Decade by 2030. Therefore, a cultural change in society is essential. Indeed, "we cannot protect something we do not love; we cannot love what we do not know"[(2)]. Certainly, ocean literacy (https://oceanliteracy.unesco.org), or the culture of the ocean, capacity building in the framework of the blue economy and innovation are part of the aims of the Institut de Ciències del Mar (ICM-CSIC), as its 70 years of work have displayed (Pelegrí 2022, Salazar *et al.* 2022). The OC-NET Programme coordinated by the ICM-CSIC together with the Unitat de Tecnologia Marina (UTM-CSIC) was endorsed on 8 June 2021 in the framework of the Ocean Decade of the IOC-UNESCO. This programme focuses on Ocean Cities[(3)] and their challenges. It is an interdisciplinary and bottom-up transformative programme. We have 10 years to react to the emergency and to relearn our relationship with the blue planet, and we should benefit from ecosystem services and ocean wealth by giving it back protection and respect.

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(1) Resolution adopted by the IOC Assembly on 29 June 2017 at its 29th Session, Paris, 21–29 June 2017

(2) Quote attributed to various authors, including Leonardo da Vinci.

(3) https://www.oceandecade.org/resource/166/Announcement-of-the-results-of-the-first-endorsed-Decade-Actions-following-Call-for-Decade-Actions-No-012020

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7.4. A civil society committed to the marine environment

Carine Simon, Magda Vila, María Vicioso, Maravillas Abad, Josep L. Pelegrí

Traditionally, research centres have acted as knowledge generators but were not asked to convey this knowledge to civil society. Fortunately, this has been changing, and research centres are increasingly committed to generating knowledge that is transformative. This is especially important for marine science research centres, which study an environment often far away from the daily reality of a large part of the public.

For several decades, the Institut de Ciències del Mar (ICM) has been committed to explaining the behaviour and importance of the marine environment to the public through numerous cultural projects and activities of dissemination and marine science communication. Many of these actions are reflected in the *ICM Divulga* educational platform created in 2005 (http://icmdivulga.icm.csic.es/). However, in this task of making the status and functioning of the marine environment known, scientific centres require the commitment and participation of the entire society.

Increasing marine science culture is crucial at a time of global change and climate emergency like the one we are currently experiencing. Habitats and biodiversity are being lost at a dizzying rate, pollution and overfishing are more the norm than the exception, invasions of exotic species are frequent, and the planet's temperature is increasing at an alarming rate, leading to a rise in sea level and a greater number of intense storms. Faced with this situation, citizens have ceased to be passive spectators and have begun to become agents for change.

Civil associations as an instrument towards change

With the aim of preserving the marine environmental heritage and reporting on the repercussions that arise from its alteration or loss, in recent years, the civil response in the form of small companies and civil associations has multiplied. Some focus on production and sustainable consumption, others on education and knowledge of the natural environment. For example, the *Mar de Ciència* (Sea of Science) association (http://mardeciencia.org/) set up in 2019 aims at bringing the reality of the marine environment closer to society through the principles of sustainability, social justice and respect for nature.

Mar de Ciència seeks to educate, disseminate and communicate, and also to raise awareness about our individual and collective need to live in connection and harmony with nature, and, especially, with the marine environment, which we often see as distant and alien. The association knows that science is necessary but not sufficient to achieve this challenge. Citizens must be coordinated to develop and demand responsible and sustainable habits of behaviour and consumption.

The *Mar de Ciència* association supports and promotes citizen participation in observing the marine environment but, above all, it carries out cultural, educational and awareness-raising activities. Like other civil entities, it participates in collaborative projects and creates opportunities for open debate and a critical spirit. In its short history, *Mar de Ciència* has participated in the creation of a meeting place between various

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Figure 1. Graphic recording prepared by illustrator Clara Tanit during an informative activity of the environmental awareness project *Operation Mar-Net, Mar-Viu*, which included a talk by Eva Calvo (ICM-CSIC) and a round table discussion.

initiatives and associations that work in Catalonia to promote knowledge and respect for the ocean (*Espai Mediterrani*, https://espaimediterrani.org/). This great ocean that surrounds our planet is a common good, in the same way that forests are a good shared by all people, without distinction. The oceans are probably the best example of how social justice and nature are inseparable.

Mar de Ciència also organizes and participates in informative and awareness-raising events, including conferences, round tables, workshops, photography contests and beach cleaning. Together with other civil entities, it supports research and citizen science projects whose final objective is to rethink our relationship with the coastal and marine environment. The association's aim is to bring society closer to the sea, to raise awareness, from a scientific perspective, on environmental problems related to the sea, and to promote changes in attitude.

Like many other initiatives and civil associations, *Mar de Ciència* expresses itself with its daily action at a local level in schools and in the neighbourhood, and it goes further thanks to social networks, especially through a website that gives a voice to the Catalan coast, with articles that make us reflect, for example, on the excessive urban use of the coastline and the environmental problems that it entails.

The main task of civil society

Civil associations are here to drive this critical mass that is necessary for change. One of the clearest forms of action is to combine knowledge (science) and the senses (art) in order to develop a notion of belonging to our natural environment. Success will be achieved by sharing experiences and sensations that lead to reflection and internalization of the ravages of global change and climate emergency. This

Figure 2. Left, beach clean-up on 12 November 2018 organized by the ICM Young Researchers association in collaboration with the *Mar de Ciència* association. Right, activities with children mixing knowledge and emotion.

involves sharing daily experiences from the society in which we live and reflecting on the one in which we want to live. All of this ranges from strenghtening local trade to better understanding which companies have fair policies towards people and the environment, as well as knowing what actions we, as citizens, can take to mitigate the impact of global change on the ocean.

The Decade of Ocean Science for Sustainable Development (Salvo 2022) emphasizes that transformation towards sustainability will only be possible with the committed participation of society. This transformation should not be imposed but should arise from the will and the conviction that it is a necessary and possible change. When a sufficiently large part of our society accepts it and acts accordingly to achieve it, the path will have begun to be drawn, and the inertia of change will grow like a great wave that will become unstoppable. This necessary combination of knowledge and conviction with emotion, this complex pairing of mind and senses, corresponds to civil society (Balagué *et al.* 2022).

Civil associations are called to play a key role in promoting the commitment and empowerment of all people, individually and collectively, towards a fairer society in harmony with nature.

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7.5. The Earth's blue heart: know it to protect it

Elena Martínez Batalla, María Vicioso

There is a directly proportional relationship between the degree of ignorance and the degree to which society acts when faced with a problem. When faced with environmental problems, instead of taking action, people sit on the sofa waiting for others to find a solution, because they believe the problems are too big for them to handle. This is especially true when the disaster is far away, but in the case of the ocean, the threats are unfortunately global.

Marine ecosystems produce a large amount of oxygen and are nature's largest reservoir of carbon dioxide. They offer refuge to a large number of species, including humans. The ocean provides us with food resources and a place to live (nearly 40% of the world's population lives in coastal areas) and acts as our greatest ally in the fight against climate change by regulating the climate that allows life on Earth as we know it. However, the human species' lack of knowledge has led it to put its own interests above those of the ecosystems, as evidenced by the fact that we know more about the Moon and Mars than we do about the system that keeps us alive: the global ocean.

"A world without the ocean is a world without us", once said the oceanographer Sylvia Earle, who resigned as chief scientist of the National Oceanic and Atmospheric Administration "because I couldn't tell you what I knew". And what we know now is that 90% of the big fish we like to eat have all but disappeared in the last 50 years because we are intelligent enough to catch them but not to understand that if we consume them before they can reproduce, we cannot consume their offspring. We also know that half of the world's coral reefs have disappeared in the last half-century (Myers and Worm 2003) and that, if nothing changes, the other half could disappear in our children's lifetime, among many other things. Yet we stay on the sofa.

It is simply not true that the ocean is sufficiently resilient to be exploited without limit. We have no choice but to act in order to save what Earle says is the "circulatory system" of the planet we live on, "the blue heart of the Earth". This system has absorbed more than 90% of the excess heat from greenhouse gas emissions and captured from the atmosphere more than 30% of the carbon dioxide emitted so far, leading to its acidification.

Knowledge for protection

For all these reasons, action must be taken to ensure the sustainability of the ocean, that is, its future beyond the current generation. This means, first of all, getting to know it, because no one is capable of protecting the unknown. Scientific dissemination and education are therefore essential in order to create a society that has the knowledge available to make critical and informed decisions based on rigour and commitment, whether in research or in transmitting to the young the importance of protecting this blue heart.

At the Institut de Ciències del Mar (ICM) we seek to promote the ocean culture or (Salazar *et al.* 2022), understood as knowledge of the mutual influence between the ocean and humanity from the early stages of learning, including knowledge of the ocean in school curricula across the disciplines instead of as a separate subject. The ocean interconnects the world,

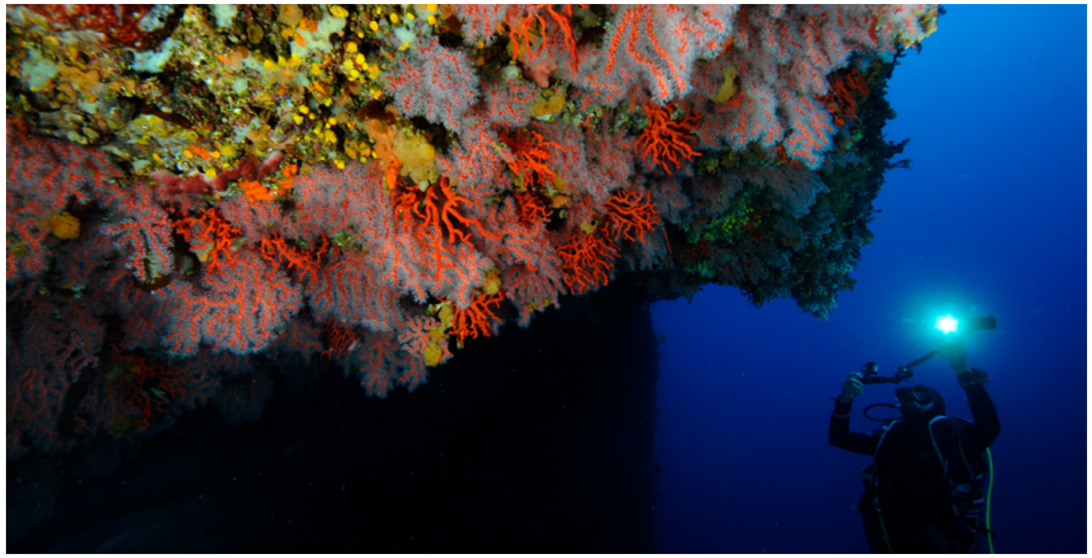

Figure 1. Lack of knowledge has led the human species to put its interests above the health of marine ecosystems, and we are already starting to witness the consequences. (Photo: J. Garrabou).

and that is how we believe it should be known. However, we also want this ocean culture to mobilize young people, who are increasingly activist, increasingly concerned about the future that awaits them, increasingly aware and willing to take action related to protection.

Finally, we cannot forget the adult public, for whom we must also provide access to knowledge, as they can take part in citizen science projects and end up becoming an active part of marine research and conservation. At the end of the day, all segments of society add up to achieve the ultimate goal: that science and the ocean become part of the shared culture of society.

With this objective, the ICM is evolving as a centre with strong local ties. In addition to sharing the results of its research with society, it is beginning to listen and generate opportunities for conversation that can enrich all parties. We want the world to put on "blue glasses", the perspective from which the ocean's link with life is understood.

There is still time

We need a change, and that change must happen now. There is still time. There is no excuse, we have the knowledge and the technology. All we lack is the will, which must come with the hope that we can find a permanent place to live, and live well, in a natural system like the earth.

"Not everyone can do everything, but everyone can do something to make a difference", said Earle, for whom "a world without the ocean is a world without us". Therefore, all that remains is to protect it. And that is why we need a great deal of interest, the kind of interest that gets us off the sofa and drives us to change our consumption habits and, by extension, our way of interacting with the natural system that keeps us alive.

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7.6. Ocean literacy: towards a science-literate society that is committed to the ocean

Janire Salazar, Josep-Maria Gili, Begoña Vendrell

Knowing and understanding the ocean's influence on us and our influence on the ocean is the essence of ocean literacy. It aims to train people to become "ocean-literate", i.e. to be aware of the ocean and therefore capable of making informed and responsible decisions on marine resources and the sustainability of the ocean and, by extension, that of the world.

This concept appeared in the United States thanks to an interdisciplinary effort by representatives of the scientific, educational and political sectors. Because the ocean had for years been excluded from scientific culture and was not suitably represented in the curricula of formal education, the aim was to produce a framework of reference agreed upon by the sectors most directly involved in improving ocean literacy and to endow this framework with specific content. This effort continued from 2002 to 2005, when a guide was published with 7 essential principles (Figure 1) and 45 fundamental concepts that everyone should know and understand in order to be considered ocean-literate (Ocean Literacy Network 2013).

Though marine knowledge can be acquired from many sources and in many ways, the Ocean Literacy guide, which is currently internationally accepted, sets the framework for outreach and educational efforts because it is aimed at different types of agents. It can also be used to create indicators for identifying and achieving objectives, and ultimately for developing strategies to attain local and global objectives of ocean literacy. The guide is recognized by UNESCO and is already part of the political agendas of many countries which are working to improve marine knowledge.

The role of marine research centres in achieving ocean literacy

Traditionally, marine knowledge has not been egalitarian but has been limited to certain sectors of the population (mainly scientists and naturalists, members of the fishing sector and boat crews). Knowledge has been transferred to the rest of society through literature and particularly through popular science events, often in coastal towns, but these efforts have been usually limited to the local level.

As a result, though it plays a fundamental role on the planet, the ocean has not been as present in formal education as it should, and

1. THE EARTH HAS ONE OCEAN WITH MANY FEATURES.
2. THE OCEAN AND LIFE IN THE OCEAN SHAPE THE FEATURES OF THE EARTH.
3. THE OCEAN IS A MAJOR INFLUENCE ON WEATHER AND CLIMATE.
4. THE OCEAN MAKES EARTH HABITABLE.
5. THE OCEAN SUPPORTS A GREAT DIVERSITY OF LIFE AN ECOSYSTEMS.
6. THE OCEAN AND HUMANS ARE INEXTRICABLY INTERCONNECTED.
7. THE OCEAN IS LARGELY UNEXPLORED.

Figure 1. The essential principles of ocean literacy. Adapted from the Ocean Literacy Network (2013).

Figure 2. *La Gymkhana dels Mars i Oceans* (The Ocean Trail) is a resource developed at the ICM that improves the ocean literacy of the more than 400 students and teachers who participate. It includes more than 72 theoretical-practical workshops, and ICM staff are involved.

this has meant that the knowledge and meaning that both the knowledge and skills which would lead to sustainable and responsible actions towards the ocean are quite absent.

Research centres and universities where marine science is carried out play a decisive role in knowledge transfer. As places where scientific knowledge is generated, they must participate in the strategies for achieving ocean literacy. Proper capacity-building of the centres so that they can carry out activities with suitable methodologies and produce attractive and effective educational and informative resources is vital if we are to progress towards a universal, high-quality ocean literacy.

The experience and future perspectives of the Institut de Ciències del Mar

The Institut de Ciències del Mar (ICM) has a long tradition of creation and development of outreach and educational content and activities. Among the main resources it has created are the onboard campaign diaries, which are highly informative and experiential and offer the added thrill of ocean exploration (Balagué *et al.* 2022). Another project, *El Mar a Fons* (The Sea in Depth), began in 2010 and has a large repository including teaching contents, educational games, an illustrated book, protocols for research activities and face-to-face workshops (Figure 2). Contents are available free of charge on the website https://elmarafons.icm.csic.es/?lang=en. These and many more examples can be found on the ICM's website dedicated to outreach and education, ICM Divulga (www.icmdivulga.icm.csic.es).

In order to meet its future educational and outreach objectives, the ICM must continue to offer resources and methodologies to further the understanding of marine ecosystems in a changing environment and introduce improvements in the transfer and exchange of knowledge. An example of this is the ICM's participation in the European project Responsible Research in Biosciences (ResBios 2020) [1], which involves experts from different fields of knowledge who belong to institutions with varied but also common characteristics. In this project, thanks to the mutual learning of the participants, actions are established with the aim of consolidating responsible research and innovation (RRI) practices in biosciences. The ICM is already working with educational establishments to form a network of marine schools as a platform for debate and learning about the best educational practices to ensure universal, high-quality ocean literacy. With this network, the ICM is creating a common, cohesive space for different actors to find resources and good practices. In the first academic year, 2020–2021, despite the difficulties added by the COVID-19 crisis, progress in this direction was made through a pilot training action in which the requests and good practices of the participating centres were used to build a community, taking into account the situations and viewpoints of each centre.

In the field of ocean literacy in society at large, the ICM is also moving from a model of transfer of information from researchers to the public towards a model of two-way transfer, in which it listens to people's concerns and interests, taking advantage of the opportunities in marine research that emerge from society.

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(1) ResBios, RESponsible research and innovation grounding practices in BIOsciences, received funding from the European Union's Horizon 2020 Research and Innovastion Programme under the Grant Agreement Nº872146.

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7.7. The sea explained through oceanographic campaigns

Vanessa Balagué, Clara Cardelús, Josep-Maria Gili, Carine Simon, María Vicioso, Magda Vila

The oceans occupy almost three-quarters of the surface of our planet and affect many aspects of our life, such as fish production, climate regulation and people's well-being and leisure. However, this importance is not transferred proportionally to the curricular content that students deal with during their education and usually remains unknown by a large part of society.

Real-time tracking of an oceanographic cruise

An attractive way to explain marine research is through real-time tracking of an oceanographic cruise. To this end, the scientific and technical teams of the Institut de Ciències del Mar (ICM) who are in expeditions at sea write a campaign diary in which they explain the scientific aspects of the ocean, how they carry out marine science and how they live on a research vessel (Simó 2017). Primary and secondary schools are specifically invited on some cruises, with the aim of putting them in direct contact with scientific and technical staff so that, guided by their teachers, they can apply the curricular content to marine sciences in an experiential and practical way. Sometimes, the ICM staff involved supplement the diary with educational activities and experimental proposals. Students can also ask questions to the scientific-technical staff on board, either through the internet or through real-time connections. This methodology is also complemented with talks in schools, teacher training and guided visits to oceanographic vessels. The diaries, as well as the questions from the schoolchildren and the responses of the on-board staff, are available to the public and are expressed amenably but with scientific rigour.

The origin of this practice goes back to several oceanographic cruises (Antarctica 2000 and 2003, Hawaii 2001 and Arctic 2004) whose diaries were published on the website of the *Agència de Gestió d'Ajuts Universitaris i de Recerca* (AGAUR). The diaries continued to be published on the *Recerca en Acció* website of the *Fundació Catalana per a la Recerca i la Innovació* (FCRI) (http://www.recercaenaccio.cat/) and are currently being recovered to be published in DIGITAL.CSIC, the repository of the Spanish National Research Council (*Consejo Superior de Investigaciones Científicas*, CSIC), which conserves and disseminates the CSIC's research results in open access (Figure 1).

The sea reaches the classrooms

Since 2004, 34 oceanographic cruises have been monitored through the ICM Divulga website (http://icmdivulga.icm.csic.es/expedicions/), and since 2015, this pioneering initiative has been an essential task of the ICM's expeditions. Seven of the 18 campaigns carried out since 2015 (Figure 1) have been specifically followed by 38 schools (29 primary schools and 9 secondary schools of 17 towns, mainly in Catalonia), reaching a total of 2,227 students and involving 88 members of the scientific and technical staff of the ICM (Figure 2).

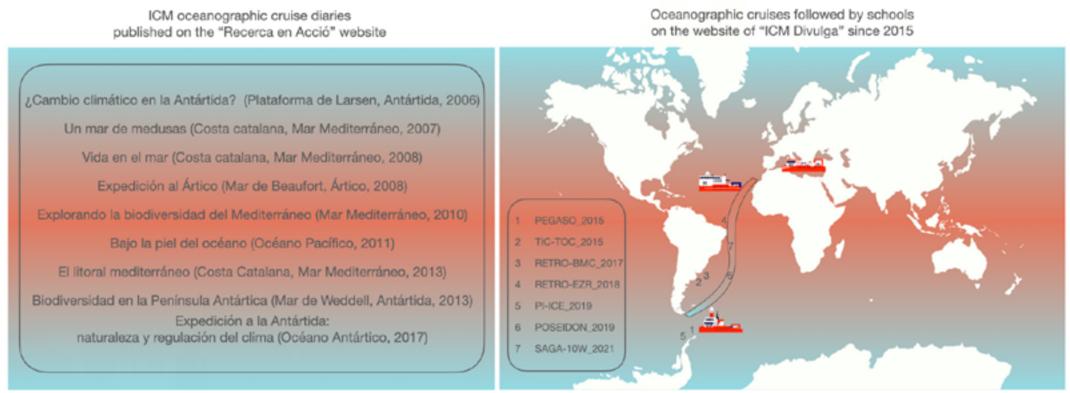

Figure 1. List of ICM oceanographic cruises published on the website of the *Fundació Catalana per a la Recerca i la Innovació* and those followed by schools on the website of ICM Divulga since 2015. Illustrations of oceanographic ships: SHOOK Studio for the *Petits Oceanògrafs* project.

The educational levels participating in the monitoring cover the stages of preschool, primary and secondary education in their entirety, although the schools aim the project at students between the fourth year of primary school and the second year of secondary school. In some cases, the project has been carried out in highly complex schools, where the teachers valued it as a very powerful educational alternative for their students.

Through the dissemination of oceanographic cruises, scientific topics are addressed from an experiential, cross-cutting and interdisciplinary perspective (Pedrós-Alió 2017). The contents cover disciplines such as life and earth sciences (physics, chemistry, biology, geology, marine sciences and astronomy), geography and history, nautical science, art and language. Issues related to the logistics and communication systems of oceanographic vessels and Antarctic bases are also discussed, as are the professions of the people linked to the cruise. Other topics dealt with include psychological and social issues such as scientific collaboration, teamwork and coexistence, and issues of current relevance such as marine pollution, the climate emergency and the role of women in science.

All this information is shown on the ICM Divulga website, from which the campaigns are disseminated and monitored, and the complete contents can be downloaded from DIGITAL.CSIC. The dissemination is reinforced with specific news on the ICM's Twitter and Instagram channels. The schools also disseminate the project through their platforms with the aim of channelling this experience to the entire educational community. The SotaZero website received the 2004 eLearning Awards (European Schoolnet of the European Union) for the Antarctic cruise web ANT XXI / 2 (2003–2004). Finally, most schools use school work on ocean-

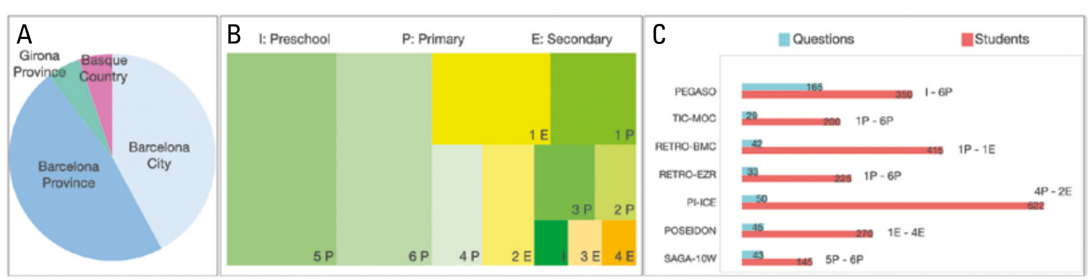

Figure 2. Results of the monitoring of oceanographic cruises by schools (ICM Divulga since 2015) according to their location (A), the educational levels that have participated (B) and the number of students and the questions asked according to the educational levels in each cruise (C). In response to the on-board staff involved in the diaries, in several projects the number of questions was limited to 50.

ographic cruises for exhibition on their open days because they see this activity as an added value to their educational projects.

Education and awareness through the diaries

This experience has been assessed as a valuable non-formal teaching resource in schools because it introduces the study of the sea, which is usually absent from curricula (Gasol 2004). On many occasions, the students have become members of the expeditions, even carrying out scientific experiments in parallel to those carried out by the staff. This project can be applied to all levels of education, but especially with 8- to 14-year-olds. The diaries offer the highly gratifying experience of sharing the experience of the sea in real time through questions, experiences and results obtained by the team on board and the participants. The project fosters curiosity, dialogue, reflection, a critical spirit and interest in science and its methods in a key stage for school and personal development, while making visible the work of professionals who study the sea, and especially the role of women in oceanography today. The concern that students have expressed about the state of the oceans is also highly appreciated. Environmental sensitivity must be dealt with effectively from the earliest educational levels. A young person who knows the sea from an early age will learn to respect it and to be actively involved in its conservation.

The result of monitoring oceanographic cruises has always been positive for both schools and research staff, who enjoy the opportunity to show their work and the research carried out at the ICM, promoting simultaneous learning between the scientific and technical staff, schools and society.

Acknowledgements: Elisabetta Broglio has been the promoter of the monitoring of oceanographic cruises on the ICM Divulga website since its beginnings. We would like to thank all the scientific and technical staff who have dedicated some of their valuable time on the cruises to writing in the diaries, answering questions and reviewing texts with scientific rigour and enthusiasm for their work and its dissemination. The cruises whose results are presented in this essay were financed by the Spanish Ministry of Science, Innovation and Universities. The FECYT *Petits Oceanògrafs* project (https://petitsoceanografs.icm.csic.es) includes the monitoring of oceanographic cruises within its objectives and five of the cruises presented were specifically followed by schools participating in this project.

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7.8. *Observadores del Mar*: transformative marine citizen science

María Vicioso, Paula López, Sandra Espeja, María García, Gemma Agell, Macarena Marambio, Joaquim Garrabou

The world, like the ocean, is global and interconnected. As we face the current social, health and climate crisis, it is clear that humanity is interrelated and that only collectively will it be able to face today's challenges and move towards a more sustainable and fairer future for people and ecosystems. As ocean currents transfer heat towards the earth's poles and distribute essential nutrients for life in the oceans, social initiatives are a transformative power capable of crossing borders and changing situations.

Citizen science is one of those concepts that can make a real change. It is a broad term that refers to the participation of the non-specialized public in scientific research either through their intellectual effort or knowledge or with their tools or resources, as defined by the White Paper on Citizen Science (Serrano Sanz *et al.* 2014). However, the definition of Caren Cooper, a recognized promoter of citizen science in ecology, makes a more accurate assessment of its real impact: "citizen science is the movement that challenges us to rethink how knowledge is made, who makes it, where it happens and who it serves". Citizen science consists of practices in which scientific research is done not only within the walls of academia by scientists, but also in many more places and by many more people simultaneously, fostering new dialogues and collaborative networks.

Transforming society with science

Citizen science initiatives can promote community participation and provide tools, training and new ways of sharing traditional knowledge. It has the potential to become an instrument for social transformation by democratizing the generation of knowledge, performing research collectively and openly, and fostering a society capable of making informed decisions.

The ocean provides resources and living space to more than a third of the world's population and is essential for the planet's stability. However, it suffers significant impacts as a consequence of climate change and human activities. Citizen science offers a channel for raising social awareness of environmental problems and promoting ocean literacy (Salazar *et al.* 2022). It is and will be the way to build bridges between scientific, political and social agents, enriching a conversation that will establish more effective conservation measures that are better accepted by society. However, marine citizen science still faces many challenges. Unlike terrestrial ecosystems, which have a consolidated community of naturalists who report observations, marine ecosystems are more difficult to access and citizens are unlikely to contribute beyond the coastal zones (García-Soto *et al.* 2017).

Watching the sea with citizens

Observadores del Mar (Sea Watchers) is an initiative carried out thanks to a constant collaborative effort. It was set up to meet people's need to communicate what they saw at the sea, to bring together the experience of sea lovers, inhabitants of the coast and groups such as fishermen and divers who witness changes in ma-

Figure 1. Marine citizen science establishes participation and communication channels between key actors for marine conservation. Photo: Jordi Regás.

rine and coastal ecosystems. Since 2012, *Observadores del Mar* has been a platform that collects and publishes people's contributions about marine problems, such as alterations in biodiversity and habitats; the evolution of vulnerable or threatened species; the effects of climate change on the marine environment; the arrival and expansion of exotic species; and the presence of marine litter. Initially, researchers from the Institut de Ciències del Mar (ICM) coordinated the project and validated the information collected. They were later joined by researchers from other marine centres of the Spanish National Research Council, such as the Center d'Estudis Avançats de Blanes (CEAB) and the Institut Mediterrani d'Estudis Avançats (IMEDEA), institutions that today co-coordinate the project together with the ICM, and other research centres and universities. *Observadores del Mar* has continued to evolve over the years, despite fluctuations in its funding, and has always maintained its potential for transformation. Today, it has more than 90 members of the scientific team, more than 3,000 volunteers and more than 300 entities such as universities, NGOs and diving clubs. It has established alliances with the Fundación Biodiversidad in the framework of the INTEMARES project and with the Fundación Marilles in the Balearic Islands, and establishes knowledge transfer channels with administrations to strengthen marine conservation with the collaboration of the public. At the gates of its tenth anniversary, *Observadores del Mar* is positioned as a benchmark marine citizen science platform in Spain and continues to generate synergies, actively participating in the growth of a community that shares the common goal of working for a healthier ocean.

In the Decade of Ocean Science for Sustainable Development (Salvo 2022) established by the United Nations for the period 2021–2031, the key challenges will be to expand the ocean observation system, to distribute data, knowledge and technology, and to change humanity's relationship with the ocean (Barbière *et al.* 2020). Marine citizen science and *Observadores del Mar* help overcome these challenges by providing open access data, technologies and tools.

They are also an inspiring model for understanding and appreciating humanity's bond with the ocean.

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7.9. Artistic rigour and scientific creativity

Vanessa Balagué, Anna Rierola, María Vicioso

The search for common metaphors for understanding the world around us comes from ancient times. Throughout the history of humanity, there have been many examples of such distant disciplines as astronomy, philosophy and poetry crossing their borders to build new knowledge and thought. However, since the 17th century scientific progress has focused on the use of reason and empirical research, and under the Cartesian and Newtonian mechanistic views there has been a trend towards specialization, fragmentation of knowledge and rejection of unregulated knowledge. Despite the inheritance of classical and modern thought, the current context of global change at the beginning of the 21st century forces us to rethink ourselves as individuals and as a collective. On a planet where nature and society are intra- and interconnected, there is a need to once more cross the borders of the different fields of knowledge. Science, philosophy and art dialogue again, blur the limits and negotiate new creative research practices (Hustvedt 2020).

A paradigm shift in contemporary art and science

During the last third of the 20th century, a great paradigm shift occurred in contemporary art: the hegemony of fine arts entered into crisis. There began a period in which research and experimentation in methodologies and procedures were placed at the centre of artistic projects and at the service of the ideas that artists wished to transmit, with messages generally linked to the social and political movements of the time. The forms of artistic expression also changed: plastic and material support was no longer essential and new languages appeared, such as action art, audiovisual art and performance art. Art is no longer based only on inspiration, and its purpose is no longer only enjoyment or emotion. It is an intellectual act with a transforming social function and is based on research, experimentation and rigorous work.

Another paradigm shift also appeared in the scientific world at the same time, linked to phenomena such as the environmental movement and the space age. Scientists found that they needed to transmit their knowledge to society, and the dissemination and communication of science emerged in parallel to scientific research. This was partly a strategy for communicating issues of environmental protection and public health, but it was also aimed at achieving a more cultured society and a larger critical mass to participate in the construction of our future. Initially, this was done through traditional formats such as documentaries, talks and informative articles, but little by little scientists made use of new formats to reach new audiences. At the Seventh Congress on Social Communication of Science (Burgos, 2019), ways of explaining the abstract concepts of science were shown through the performing arts, cinema, games, music, literature, unconventional exhibitions and street art. The purpose of science is therefore not limited to discovering, understanding and explaining the findings among professional colleagues, but includes sharing knowledge with an increasingly participatory society that wishes to be better informed.

Overall, rigour and creativity are shared values between science and art. For example, the

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Clean ocean
Healthy and resilient ocean
Productive ocean
Predictable ocean
Safe ocean
Accessible ocean
Inspiring and engaging ocean
Indexes

Harmonic development with nature
Mission Starfish 2030
Ocean Decade
Committed to the marine environment
The Earth's blue heart
Ocean literacy
The sea explained through oceanographic campaigns
Observadors del Mar
Artistic rigour and scientific creativity

Figure 1. Dialogues between music, dance, art and science at the opening of the exhibition *Ancestral Forest* by Anna Rierola (2017) at the Centre Mediterrani d'Investigaciones Marines i Ambientals (CMIMA).

artist's notebooks of Fina Miralles are like lab notes and recent scientific theories such as James Lovelock's Gaia and Lynn Margulis's Symbiogenesis are great sources of inspiration and have an undeniable visual and conceptual aesthetics. Furthermore, in both contemporary art and science, the transformation and construction of knowledge and thought are fostered by questions, conflicts, ideas, curiosity, rigour, creativity and research (Tafalla 2011).

Art&Science and *Ancestral Forest*

The desire to create global knowledge recently gave rise to Art&Science (ArtSci), a new collaborative movement that brings together a community of artists, scientists, technologists, programmers, philosophers and cultural agents in which enriching alliances are generated to carry out interdisciplinary projects. Some scientists find in art a way to represent their data and link it to an environmental, political or social message, and some artists find in science their inspiration, the initial material and the theoretical support for their work. Centres such as the CCCB and Arts Santa Mònica and festivals such as Sónar, Eufònic, Llum BCN and Ars Electronica have become showcases for these new interactions (Kourochkina 2021).

An example of these synergies is *Ancestral Forest*, the first large-format work arising from the collaboration between Anna Rierola[(1)], a visual artist specializing in scientific images, and the Electron and Optical Microscopy Service of the Institut de Ciències del Mar (ICM-CSIC)[(2)]. The exhibition (Figure 1) was accompanied by information panels and a series of conferences on the protagonists of the mural: marine microorganisms and their crucial role on the planet[(3)]. This temporary exhibition gave rise in 2019 to a 60-metre outdoor mural that covers the façade of the ICM headquarters and has become part of its visual identity: a new window for the city and its visitors (Figure 2). Reflecting the sea from the Somorrostro beach in Barcelona, it shows that the immensity of the ocean contains the unseen essential processes that sustain life on Earth, and it is this awareness that must help us leave the Anthropocene era behind.

Interdisciplinary and heterogeneous dialogues, social transformation engines

The seas and oceans are the engine of change and life. Everything that happens on land is connected to the sea: the exchange of energy, matter and information. In the current context of global change, it is crucial for citizens to understand these processes, because only through knowledge can awareness be raised and collective action systems activated. Reaching everyone is not easy. It involves exploring new formats for disseminating knowledge and collaborating with professionals from other fields. One option is to set up artistic residencies in scientific research centres, promoting co-creation in addition to consultation and data transfer. Another is to promote opportunities for debate and joint reflection, with a heterogeneous participation in

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Committed to the marine environment
The Earth's blue heart
Ocean literacy
The sea explained through oceanographic campaigns
Observadors del Mar
Artistic rigour and scientific creativity

Figure 2. *Ancestral Forest* by Anna Rierola (2019), a mural created from electron microscopy images of marine microorganisms provided by the Institut de Ciències de Mar and of nanomaterials and synthetic polymers provided by the Institut Català de Nanociència i Nanotecnologia.

terms of disciplines, generations and social and cultural actors. Based on mutual respect, the participants can find common metaphors for understanding and explaining the world, our way of being and our way of inhabiting it. The commitment of a research institute of excellence such as the ICM to continue promoting this type of rigorous and creative collaboration with artists and thinkers is essential to provide feedback and broaden the transmission channels and target audiences of our messages and values (Figure 2).

Acknowledgements: We thank José Manuel Fortuño, head of the Electron and Optical Microscopy Service of the Institut de Ciències del Mar (CSIC) for his unique vision for capturing the beauty hidden inside the invisible ocean and providing the images for *Ancestral Forest*. We are grateful to Elisa Berdalet, Clara Cardelús, Lluïsa Cros, José Manuel Fortuño, Esther Garcés, Josep M. Gasol, Ramon Massana, Carles Pedrós-Alió, Rafel Simó and Dolors Vaqué for their scientific advice for the drafting of the outreach content that accompanied the exhibition *Ancestral Forest*.

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COG, Centro Oceanográfico de Gijón, IEO, Spain
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Thematic index

Opening
Clean ocean
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Productive ocean
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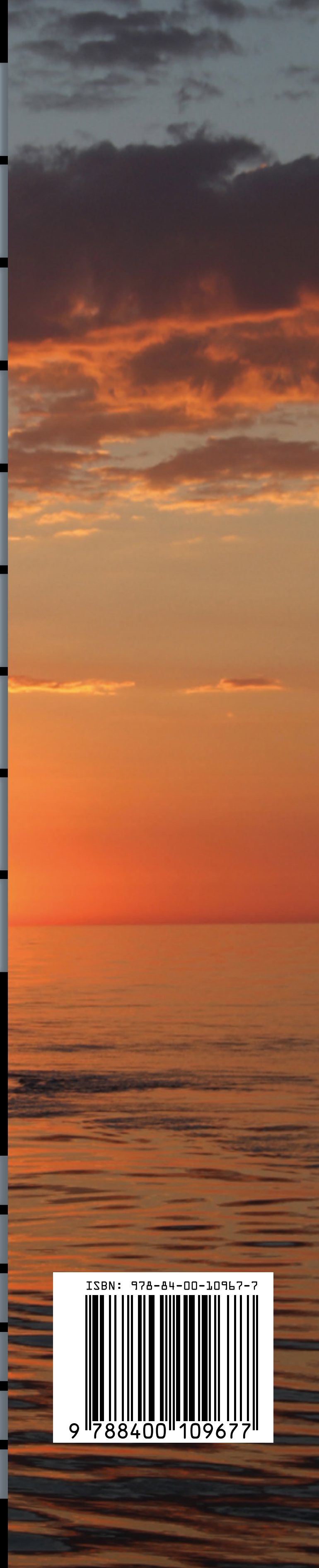

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