Navigating the Future V

Position Paper 24

Marine Science for a Sustainable Future

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Navigating the Future V: Marine Science for a Sustainable Future
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Foreword

In the six years since Navigating the Future IV was published (European Marine Board, 2013) there have been significant changes in the perceptions and realities of marine science. Worldwide, the importance of the ocean and the impact of human activities have been highlighted politically in the UN World Ocean Assessment (2015), through the adoption of "Life below the Water" as one of the UN Sustainable Development Goals (SDG14) and in the First IOC-UNESCO Global Ocean Science Report (2017). The G7 first made the future of the seas and oceans a priority in 2015 and this was emphasised again in the Tsukuba Communiqué (2016), the Turin Communiqué (2017) and the G7 BluePrint on Healthy Oceans and Seas (2018). Other highlights include the OECD Ocean Economy in 2030 report (2016) and the Our Ocean Conferences, which have taken place annually since 2016.

The human impact on the ocean has gained mainstream societal attention through the "Blue Planet effect", which has influenced ocean activists from across Europe and the world. The European Commission has now appointed a Special Envoy on Maritime Policy (MEP Gesine Meissner) and hosted a European Parliament conference on the Future of the Oceans. During the last six years, European policies have moved on from the Integrated Maritime Policy (2012) and the Marine Strategy Framework Directive (2008) to the reform of the Common Fisheries Policy (2014) and the Blue Growth agenda in support of the blue economy (2017). The European Framework programme Horizon 2020 had specific "Blue Growth" calls and the European Maritime and Fisheries Fund (EMFF) invested €6.4 billion in the maritime economy. Given these substantial developments, one could wonder whether more research is needed. Do we now know enough to be able to manage the oceans sustainably?

Navigating the Future V (NFV) shows that this is certainly not the case. There are still gaps in our knowledge from fundamental geology, physics, biogeochemistry and biology. This knowledge is critical in understanding the four-dimensional ocean, to predict tsunamis and the impact of multiple stressors on biogeochemistry and biology, and to understand the impact of the future blue economy on our marine ecosystems. NFV shows that we need transdisciplinary science and sustainability science to address the management of a holistic four-dimensional ocean. It also highlights the technological advances and modelling needed for a possible future virtual ocean that would enhance public engagement and understanding of the ocean. NFV proposes the science we need for the forthcoming UN Decade of Ocean Science for Sustainable Development (2021-2030), the next European Framework Programme, Horizon Europe, and its probable Mission on Healthy Oceans, Seas, Coastal and Inland Waters.

I hope that Navigating the Future V will enhance the uptake of ocean science throughout the UN Decade, Horizon Europe and the Mission, but also through National strategic research priorities and Joint Programming Initiatives such as JPI Oceans. I would like to thank all authors and reviewers for their contributions to this document. I would also like to thank past and present members of the European Marine Board secretariat for their work in preparing this report, including former director Niall McDonough and Senior Science Officer Kate Larkin, who are no longer at the EMB secretariat but who contributed to the formation of NFV.

Jan Mees

Chair, European Marine Board

June 2019

Prologue – Ocean Science in Action

The European Marine Board is approaching 25 years of tireless activity. Since its inception and through its changing organizational forms the European Marine Board has taken on a gradually bigger and more important role. Navigating the Future IV from 2013 and the related Rome Declaration from 2014 broke new ground in many ways, advocating observations and data sharing for multiple purposes and setting the stage for ocean literacy. It provided advice to the EU and to national science funding priorities, but it also stimulated the marine science community to break down barriers between disciplines and stakeholders and to talk to people at large, not only within narrow scientific circles.

The present edition offers an update and takes a perspective from now until 2030, the time frame agreed by all members of the United Nations to be crucial for a sustainable future. Within the next decade, the goal is to provide nutritious food, clean energy, water, medical services and decent living conditions for all people on Earth in a sustainable way, i.e. without overstepping the carrying capacity of the planet. Few believe that this can be done without harvesting more from the ocean and increasing activity at sea. Yet, the ocean and its ecosystem services are under threat from pollution and climate change.

Ocean science based solutions are needed and they are needed fast. Open innovation, sharing of knowledge best practices and collaboration will be imperative. Navigating the Future V is coming at exactly the right time. It puts Europe in the global context. It invites and encourages European governments, institutions and individuals to play a leading role in putting ocean science to work for our global common future. This is not a race where the aim is to leave others behind. On the contrary, now is the time to lead by example. The future we all want requires a healthy ocean and sustainable use of its resources. This report is a step towards the science we need for the ocean we want.

Peter M. Haugan

Chair, Intergovernmental Oceanographic Commission (IOC of UNESCO)

Executive Summary

Navigating the Future is a publication series produced by the European Marine Board providing future perspectives on marine science and technology in Europe. Navigating the Future V (NFV) highlights new knowledge obtained since Navigating the Future IV[1] (2013). It is set within the framework of the 2015 Paris Agreement[2] and builds on the scientific basis and recommendations of the IPCC reports[3]. NFV gives recommendations on the science required during the next decade to deliver the ocean we need to support a sustainable future. This will be important for the United Nations Decade of Ocean Science for Sustainable Development[4] (2021 – 2030), the implementation of the UN Sustainable Development Goals[5] and the European Commission's next framework programme, Horizon Europe[6] (2021 - 2027). There is a growing need to strengthen the links between marine science, society and policy since we cannot properly manage what we do not know.

In recent years, the ocean and seas have received new prominence in international agendas. To secure a safe planet a priority is the management of the ocean as a "common good for humanity", which requires smarter observations to assess of the state of the ocean and predictions about how it may change in the future. The ocean is a three-dimensional space that needs to be managed over time (thus four-dimensional), and there is a need for management and conservation practices that integrate the structure and function of marine ecosystems into these four dimensions (Chapter 2). This includes understanding the dynamic spatial and temporal interplay between ocean physics, chemistry and biology. Multiple stressors including climate change, pollution and over-fishing affect the ocean and we need to better understand and predict their interactions and identify tipping points to decide on management priorities (Chapter 3). This should integrate our understanding of land-ocean-atmosphere processes and approaches to reducing impacts. An improved science base is also needed to help predict and minimize the impact of extreme events such as storm surges, heat waves, dynamic sea-floor processes and tsunamis (Chapter 4). New technologies, data handling and modelling approaches will help us to observe, understand and manage our use of the four-dimensional ocean and the effect of multiple stressors (Chapter 5).

Addressing these issues requires a strategic, collective and holistic approach and we need to build a community of sustainability scientists that are able to provide evidence-based support to policy makers within the context of major societal challenges (Chapter 6). We outline new frontiers, knowledge gaps and recommendations needed to manage the ocean as a common good and to develop solutions for a sustainable future (Chapter 7). The governance of sustainability should be at the core of the marine research agenda through co-production and collaboration with stakeholders to identify priorities. There is need for a fully integrated scientific assessment of resilience strategies, associated trade-offs and underlying ethical concepts for the ocean, which should be incorporated into decision support frameworks that involve stakeholders from the outset. To allow the collection, processing and access to all data, a key priority is the development of a business model that ensures the long-term economic sustainability of ocean observations.

[1] http://www.marineboard.eu/navigating-future
[2] https://unfccc.int/sites/default/files/english_paris_agreement.pdf
[3] https://www.ipcc.ch/reports/
[4] https://en.unesco.org/ocean-decade
[5] https://www.un.org/sustainabledevelopment/sustainable-development-goals/
[6] https://ec.europa.eu/info/research-and-innovation/strategy/support-policy-making/support-eu-research-and-innovation-policy-making/evaluation-impact-assessment-and-monitoring/horizon-europe_en

1 Introduction

Credit: Ferdinando Boero

1.1. Role and relevance of the ocean

The ocean's ever-changing seascape and its unexplored depths capture our imagination. It plays a crucial role in climate regulation and sustaining life. It provides humanity with significant living, mineral and energy resources and increasingly delivers our goods on a global seaway. Coastal spaces attract a growing human population who enjoy their health benefits, beauty and opportunities for tourism, leisure and for work in multiple economic sectors. However, the ocean and the essential resources it provides are under threat. We are currently living in what has been termed 'The Anthropocene' — an age in which human activities are having a dominant influence on climate and the environment. The predominant human impact is anthropogenic greenhouse gas emissions causing ocean warming and acidification. This has consequences for marine biodiversity, weather patterns (including heat waves, coastal flooding and extreme events) and the ability of the ocean to store excess atmospheric carbon dioxide (CO_2) and to produce oxygen to support life. The impact of humans on the environment is evident and studies have linked human migration to environmental degradation from climate change and other anthropogenic impacts (Leighton, 2006; Lu *et al.,* 2016). As we are facing these imminent threats to the marine environment, we are also still developing the technology and scientific knowledge base necessary to fully explore, observe and understand the ocean. These developments are needed to accurately predict and manage the impact of human activities on our future ocean.

The ocean contains most of the water on Earth and covers 71% of the planet's surface. However, only less than 10% of the world's seafloor has been mapped so far with adequate detail[7]. To fully understand its true significance, we must understand that the ocean is not merely a surface, but a volume (1,370 million km^3) representing 99% of the habitable space on the planet. In spite of the overwhelming importance of the aquatic component of the biosphere, much less is known about the ocean than the land, mainly because humans are terrestrial, and we view things from a land-based perspective. We see the fields, the forests and the stars, but we cannot see under the surface of the sea. We instinctively recognize and understand the landscape but not the seascape. This is also true for the sciences that study the ocean. For example, we often use spatial principles from terrestrial ecology and only study the sea bottom, disregarding the volume of water above.

Credit: NASA

The ocean covers 71% of the planet's surface and represents 99% of its habitable space.

The ocean has played a key role in the history of our planet and in the origin and evolution of life, and today's ocean continues to be a major actor in the support of life and the regulation of climate. Despite occupying the largest habitable space on Earth, known marine species make up only 13% of the current described world biodiversity largely due to our lack of knowledge of the depths of the ocean and of marine microorganisms.

The ocean is the largest living space on Earth and spatial continuity is its main feature. Unjustifiably, it is often misconceived as unlimited in resources, life-sustaining space and capacity to cope with anthropogenic threats. With the human population set to grow to more than 11 billion by 2100 (United Nations, 2017), this misconception increases the risks of overexploitation leading to irreversible loss of the ocean's services and benefits for society (Austen *et al.,* 2019).

The ocean plays a major role in regulating the Earth's climate by redistributing and absorbing heat: 93% of the excess energy stored by the Earth in the past 50 years as a consequence of increases in greenhouse gas emissions is found in the oceans (IPCC, 2013). This is because the capacity of the ocean to store heat is much higher than the atmosphere. Since 1993, the ocean heat content has increased at a rate of 0.6 Wm^{-2} down to 2,000 m (Schuckmann *et al.,* 2016). The ocean is stratified (layered), meaning that lighter, warmer water is found above colder, denser water. Anthropogenic warming increases the temperature of surface waters the most, which leads to reduced vertical mixing of nutrients and a decline in upper ocean productivity. Stratification also increases deoxygenation and hypoxia, which has been linked to mass extinctions in previous geological periods (Penn *et al.,* 2018) although this is not predicted in the near future.

The ocean is also an important carbon sink absorbing at least a quarter of the anthropogenic carbon dioxide (CO_2) emissions from fossil fuels and industry, with ocean acidification as an unwanted consequence. The ocean does not absorb heat and CO_2 uniformly. It varies in both space and time, with larger changes in Polar regions.

Life began early in the ocean and it has continued to prosper and evolve providing many resources including vast biological productivity from the poles to the equator. The primary production in the Polar regions supports substantial secondary production of plankton, krill and planktivorous fish. These resources have supported fisheries for food and lipids (e.g. whales, krill, etc.) for millennia.

The ocean is also a source of innumerable products and services, such as >25,000 molecules of pharmacological or cosmetic interest

[7] https://seabed2030.gebco.net/

(Blunt *et al.,* 2018) including key anti-cancer molecules produced by microorganisms and invertebrates, and some extremely relevant biochemical mechanisms with biomedical and agricultural applications e.g. marine enzymes for biocatalysis (Trincone, 2013). Marine organisms also provide insight into key biological processes including the discovery of the molecular basis of memory in sea slugs and the transmission of nerve impulses in squid. (Ye *et al.,* 2012, Hodgkin & Huxley, 1952). With only 270,000 marine species described to date, we need to increase research effort on marine biodiversity to make sure we can continue to discover other important products and services.

Credit: Mert Gokalp

Coastal habitats, such as seagrass beds, are important for climate change mitigation and adaptation as they absorb and store CO_2 and offer coastal protection.

Coastal environments support bioremediation of heavy metals, detoxification of pollutants and recycling of excess nutrients due to abundant plankton and kelp. Coastal habitats are commonly exploited for aquaculture including finfish, shellfish and algae farms. Coastal areas are also important for climate change mitigation through the growth and restoration of coastal habitats that absorb and store CO_2 including seagrasses beds, salt marshes and mangrove forests. They also offer coastal protection through soft engineering practices such as restoration of salt marshes and mangrove habitats.

Vast amounts of mineral and energy resources (e.g. massive polymetallic sulphides, cobalt-rich ferromanganese crusts, polymetallic nodules, phosphorites) are found in the ocean depths, particularly in areas beyond national jurisdiction. These raw materials have been identified by the European Commission as essential for Europe's economy and greener technologies[8] and also recognized as important by nations and industry globally. Besides marine minerals and conventional oil and gas occurrences, gas hydrates found in many areas of the globe may also become a potential alternative energy source in the future and the full impacts of their exploitation need to be fully assessed. However, the precautionary approach dictates that given the potential negative environmental impacts, prior to exploitation adequate legislation, environmental impact assessments, continuous monitoring and pilot test studies are needed.

Credit: Mert Gokalp

Mediterranean pink tube sponge. Marine invertebrates are valuable sources of bioactive compounds.

[8] https://ec.europa.eu/transparency/regdoc/rep/1/2017/EN/COM-2017-490-F1-EN-MAIN-PART-1.PDF

Credit: ©VLIZ

Spilhaus projection map showing the world's oceans as a unified body of water. Map created using world continents dataset projected to Spilhaus Oceanographic Conformal projection in G. Projector. Data source: Esri, Global Mapping International, US Central Intelligence Agency (The World Factbook).

Throughout human evolution, civilization has developed strategies to increase its resilience to threats from the ocean and has used the opportunities offered by the ocean to increase the resilience of humanity (Figure 1.1). However, the rush for coastal recreation and access to the ocean has led to newly built infrastructure that is vulnerable to extreme events. Destruction of natural coastal protection such as mangroves, wetlands or healthy reef systems has increased the vulnerability of coasts to strong winds and associated storm surges, and modified other supporting and regulating ecosystem services that depend on these habitats. This includes the resilience related to biodiversity.

Focus areas for the EU Blue Growth agenda[10], such as offshore wind farms and other marine renewable technologies including tidal turbines, wave energy devices and thermal energy, are important in the global fight against climate change. Interest in other uses of the ocean has also increased in recent decades e.g. desalination and maritime transport. A key challenge of the Anthropocene is to understand the environmental and economic consequences of the use of marine resources since the effects of exploitation are not yet well described. We do not yet fully understand how overexploitation of fish stocks or any other living or non-living resources may erode marine natural capital. There are also societal challenges including the acknowledgement that humanity is responsible for the degradation of the Earth's system and the political challenge in deciding the short-term sacrifices needed to ensure the long-term persistence of environmental conditions suitable for humanity.

1.2. Governance of ocean and coasts in the international agenda

In terms of governance, there are many options to address the challenges of the Anthropocene. Some suggest improving existing international and national rules of governance and legislation and

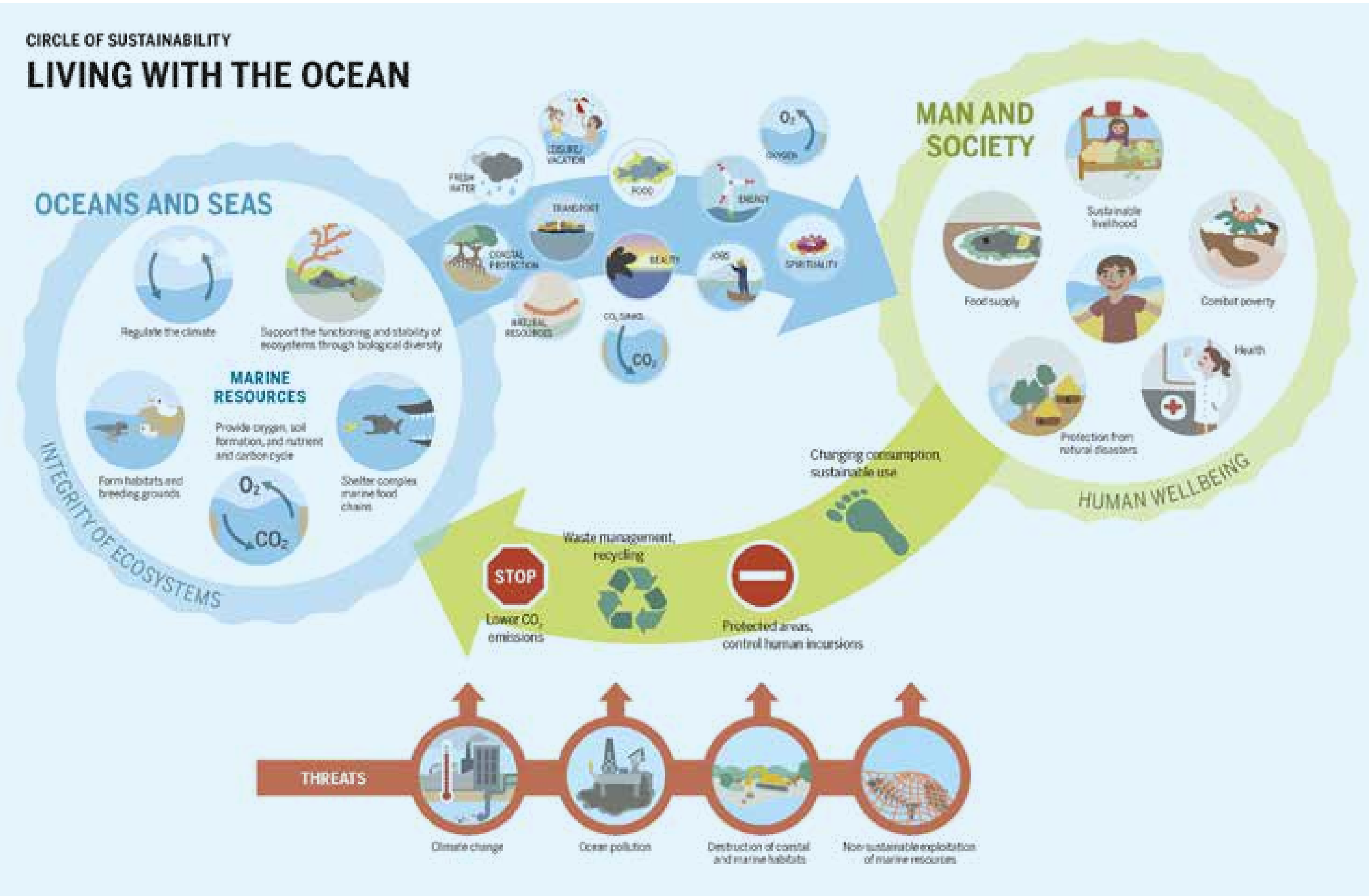


Figure 1.1. Overview of interactions between human activities and the ocean in the circle of sustainability. Ocean Atlas 2017[9]

[9] https://www.boell.de/sites/default/files/web_170607_ocean_atlas_vektor_us_v102.pdf?dimension1=ds_ocean_atlas

[10] https://ec.europa.eu/maritimeaffairs/policy/blue_growth_en

Credit: ©VLIZ

Offshore wind farms, such as those shown here in the North Sea off Belgium, are important in the global fight against climate change.

stress participatory democracy, others advocate for creating new specialized institutions with mandates to tackle functional (e.g. practical and technical) challenges, while others argue that new technologies should be invented to cope with our impacts on the environment. The reality is that a mix of all these options and more are required to address these challenges. Global actions are needed because the ocean is connected and action taken in one place will have global consequences.

The most important governance instrument to prevent irreversible negative change to the ocean is the 2015 Paris Agreement[11] in which nations have agreed on binding emissions targets to limit global warming to 2°C and if possible 1.5°C above pre-industrial levels; a scenario for which it is necessary to reach zero CO_2 emissions within the next few decades. Navigating the Future V is set within the framework of the Paris Agreement and the European Marine Board fully supports its scientific basis (IPCC reports) and its objectives.

The importance of the ocean and ocean science in the international agenda was fully recognized by the United Nations (UN) in 1960, with the establishment of the Intergovernmental Oceanographic Commission at UNESCO (IOC-UNESCO[12]). Since its creation, the IOC-UNESCO has promoted international cooperation and coordinated research, global ocean observation, data exchange and capacity-building programmes, which help with decision-making processes of its 149 Member States. In recent years, the UN has negotiated a global agreement on the exploitation of biological resources beyond national jurisdiction and has included Life Below Water (SDG14) in the Sustainable Development Goals of the 2030 Agenda for Sustainable Development (Figure 1.2). Through the G7 Blueprint on Healthy Oceans and Seas (G7, 2018), industrialized countries have also addressed ocean pollution, especially plastics, and ocean observation. The importance of science in understanding the state of the ocean is a focus of the Intergovernmental Panel on Climate Change (IPCC) 'Special Report on Ocean and Cryosphere in a Changing Climate' (to be published later in 2019), the UN World Ocean Assessment (United Nations, 2016), and the UN report on Oceans and the Law of the Sea (United Nations, 2019). The specific role of science in understanding, exploiting and protecting the oceans is the focus in the Organisation for Economic Co-operation and Development (OECD) report on 'Rethinking Innovation in the Ocean Economy' (OECD, 2019) and the IOC-UNESCO Global Ocean Science Report (UNESCO, 2017).

States have agreed that science has a special role in understanding and protecting the ocean, but often fail to agree on binding targets for its protection. This trend is both encouraging and worrying insofar as science is ideally equipped to better

[11] https://unfccc.int/sites/default/files/english_paris_agreement.pdf

[12] http://www.ioc-unesco.org/

Figure 1.2. The United Nations Sustainable Development Goals.

understand the ocean and to offer advice on the impacts of human decisions and actions, but it is not the role of ocean science to spearhead ocean protection. Science also sits at the nexus of the blue economy, which depends critically on scientific data for sustainability. In December 2017, following a proposal from the IOC-UNESCO, the UN proclaimed the Decade of Ocean Science for Sustainable Development (2021-2030)[13]. The aim is to support efforts to reverse the current decline in ocean health by bringing together ocean stakeholders worldwide to ensure that ocean science supports the sustainable development of the ocean within the context of the 2030 Agenda for Sustainable Development. The UN Decade of Ocean Science has given the marine science community a massive opportunity to present to States and societies what the ocean can offer, as well as its limits. The European Marine Board offers a platform for debating and promoting the role of ocean science and its recommendations in global sustainable development.

1.3. Europe at the forefront of ocean science and observation

The recent political drive to change the use of the ocean requires balancing the expectation of increasing the use of ocean resources while preserving environmental quality to ensure an equitable future and meet environmental targets. This is manifested through European policies (European Union (EU) Integrated Maritime Policy (COM(2007) 575)/ Blue Growth agenda (COM(2012) 494)) implemented at the national level, for example in Ireland through the Harnessing Our Ocean Wealth Integrated Marine Plan (Irish Government, 2012) and the Scottish Government's National Marine Plan[14]. These policy examples are all framed in the context of sustainable development, increasing awareness of the importance of our ocean as an economic resource, public interest in issues such as marine litter, fisheries discards, marine protected areas and the requirement to monitor and assess the health of our ocean. Monitoring is promoted internationally, for example, through the Regional Seas Conventions and at a European level through the Marine Strategy Framework Directive[15] (MSFD) (2008/56/EC).

The countries of Europe have long been aware of the benefits of the ocean and of the need to build scientific knowledge in order to realize their full potential in a sustainable way. The ocean and coasts have become more important in wider European platforms such as the European Academies Science Advisory Council (EASAC), as reflected in their report on 'Marine Sustainability in an Age of Changing Oceans and Seas' (Thiede *et al.*, 2016). They have also been recognized as important for human health (Box 1.1) including through the "Blue Gym" effect (White *et al.*, 2016).

[13] https://en.unesco.org/ocean-decade
[14] https://www.gov.scot/publications/scotlands-national-marine-plan/
[15] http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm

BOX 1.1. OCEANS AND HUMAN HEALTH

Oceans and Human Health (OHH) is a wide topic of research, which seeks to understand the complex interactions between ocean health and human health in order to maximize the benefits and minimize the risks for both humans and the ocean. It is by nature a transdisciplinary field, requiring collaboration between experts from the marine, medical and public health sectors, as well as from social sciences, psychology, law, economics and many other areas.

OHH as a meta-discipline for under-standing the complex linkages between ocean health and human health is now recognized and accepted as a key area of research. This work originated in the USA, where the focus has mainly been on harmful algal blooms and marine biotechnology. OHH was brought to the attention of the wider European research community in 2013 by the European Marine Board (Moore *et al.*, 2013). Following this publication, momentum behind this meta-discipline grew, with references in Navigating the Future IV (European Marine Board, 2013), EurOCEAN 2014 (European Marine Board, 2014a) and the Rome Declaration (European Marine Board, 2014b). This led to a dedicated conference in Bedruthan, Cornwall, UK, followed by the publication of 'Message from Bedruthan' (Fleming & McDonough, 2014) and 'Oceans and Human Health: A rising tide of challenges and opportunities for Europe' (Fleming *et al.*, 2014). JPI Oceans also included a pillar on OHH in their Strategic Research and Innovation Agenda (JPI Oceans, 2015).

The Oceans Meeting 2017 also acknowledged the importance of OHH with its main theme "The Ocean and Human Health"[16]. The combination of these calls contributed to the European Commission's Directorate-General for Research and Innovation funding a coordination and support action project on OHH, named Seas, Oceans and Public Health in Europe (SOPHIE)[17], as well as other related projects, including BlueHealth[18] and Sea Change[19].

The SOPHIE project will lay the foundation for the Oceans and Human Health research community in Europe, which you can join on LinkedIn[20]. SOPHIE will produce a Strategic Research Agenda, which will highlight key research gaps that need to be addressed to further OHH research in Europe, to be published in March 2020.

[16] https://ec.europa.eu/commission/commissioners/2014-2019/moedas/announcements/oceans-meeting-international-conference-ocean-and-human-health_en

[17] https://sophie2020.eu/

[18] https://bluehealth2020.eu/

[19] http://seachangeproject.eu/

[20] https://www.linkedin.com/groups/12127491/

1.4. The relevance of Navigating the Future series

The European Marine Board has informed European policy by producing a series of foresight reports since 2001 – the 'Navigating the Future' series[21]. The importance of society and citizens have been highlighted since the first Navigating the Future report (NFI, ESF Marine Board, 2001). NFI proposed a Marine Science Plan to promote public awareness, appreciation and education on the scientific challenges of the ocean. Navigating the Future II (NFII, ESF Marine Board, 2003) proposed that the European marine scientific community becomes more proactive in public debates concerning the marine environment and Navigating the Future III (NFIII, Marine Board - ESF, 2006) asked that marine scientists should take responsibility for disseminating scientific information on issues of societal concern. Navigating the Future IV (NFIV, European Marine Board, 2013) also advocated for an increase in ocean literacy and a more effective European marine science-policy interface as well as training the next generation of marine experts. These chapters of NFIV have been expanded upon in the European Marine Board Position Paper N° 23 on "Advancing Citizen Science for Coastal and Ocean Research" (Garcia Soto *et al.,* 2017) and Future Science Brief N° 2 on "Training the 21st Century Marine Professional" (Vincx *et al.,* 2018). This long-term vision has finally born fruit with the European Commission now proposing an EU Ocean Alliance, which will boost ocean literacy in Europe through the federation of a European network of Blue Schools and the establishment of a European Youth Forum for the Ocean.

Ocean governance is another overarching subject that was previously recommended by NFII (2003): "Europe needs to move towards sound and true governance of its oceans and seas, integrating all components for a comprehensive and responsible management of its marine assets". NFIII (2006) mentions the importance of the Galway statement[22], the European Commission's then Green paper on Maritime Policy, the need for marine resource management at a regional level, and recommends that: "A forum of marine scientists, policy makers representatives from industry, coastal stakeholders and associations should be convened regularly to ensure effective communication and synergy between sectors." NFIV (2013) also reiterated the importance of the science-policy interface and this persistence paid off with Commissioner Vella (European Commission Commissioner for Maritime Affairs and Fisheries) meeting with Marine Research Institute directors to discuss issues of ocean governance[23]. The Commission has also now, through a European Maritime and Fisheries Fund tender, proposed an International Ocean Governance Stakeholder Forum, which will hopefully address these long-standing recommendations from NFII, III and IV.

Credit: European Marine Board, Vivian Hertz

Launch of Navigating the Future IV in 2013. Niall McDonaugh, EMB Executive Secretary, Maria de Graça Carvalho, MEP and European Parliament Rapporteur for the Horizon 2020 Programme, Máire Geoghegan-Quinn, EU Commissioner for Research, Innovation and Science, and Kostas Nittis, European Marine Board Chair.

21 http://www.marineboard.eu/navigating-future

22 https://ec.europa.eu/research/iscp/pdf/galway_statement_atlantic_ocean_cooperation.pdf

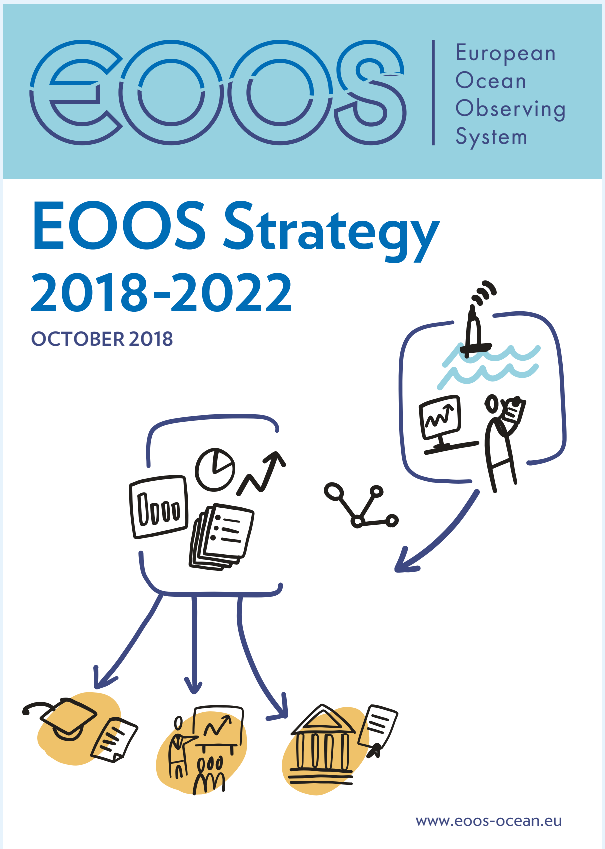
23 https://webgate.ec.europa.eu/maritimeforum/en/node/4189, http://www.marineboard.eu/commissioner-vella-meets-european-ocean-reasearch-leaders-third-time

BOX 1.2. EUROPEAN OCEAN OBSERVING SYSTEM

Europe has invested significant funding in ocean observation, and as a result the marine scientific and ocean observation community contributed greatly to the development of an Atlantic Ocean observation capability and wider marine research agendas in the Atlantic and other seas e.g. the Horizon 2020 project AtlantOS[24]

Ocean observations have been an important link throughout the European Marine Board's Navigating the Future series and the flagship marine science policy EurOCEAN conference series, which provided recommendations and inputs for strengthening pan-European ocean observing coordination. The 2010 Ostend Declaration[25] included a proactive and integrating action to "support the development of a truly integrated and sustainably funded European Ocean Observing System (EOOS)". This was taken forward into Navigating the Future IV (European Marine Board, 2013) with a dedicated chapter on the EOOS and the need for a cyclical, regular process of implementation. EurOCEAN 2014's Rome Declaration[26] included a specific call for "further development of the EOOS, integrated at the global level (including the Global Ocean Observing System (GOOS), Group on Earth Observations (GEO) and Copernicus)." Since then, European ocean observing communities have worked together to answer this call and turn EOOS into a reality.

These developments paved the way for EOOS: a coordinating framework to align and integrate Europe's ocean observing capacity, to promote a systematic and collaborative approach to collecting information on the state and variability of our seas, and to underpin sustainable management of the marine environment and its resources. The European Global Ocean Observing System (EuroGOOS)[27] and the European Marine Board jointly promoted EOOS to connect the operational oceanographic and wider marine scientific communities and to stimulate the transition of EOOS from a visionary concept into a tangible initiative. This has led to the community approved Strategy and Implementation Plan 2018-2022[28], launched at the 2018 EOOS Conference[29].



24 https://www.atlantos-h2020.eu/
25 http://www.euroceanconferences.eu/eurocean-2010
26 http://www.euroceanconferences.eu/eurocean-2014
27 http://eurogoos.eu/
28 http://www.eoos-ocean.eu/strategy-and-implementation/
29 http://www.eoos-ocean.eu/conference-2018/

NFIV (2013) identified emerging research topics in marine science and technology in relation to major societal challenges: feeding humanity, energy, mineral resources, health, adaptation to climate change, preservation of biodiversity, and safe and sustainable use of marine and coastal spaces. European-funded research projects have been developed, or are currently underway, to address these societal challenges as part of Horizon 2020[30], the Joint Programming Initiative Healthy and Productive Seas and Oceans (JPI Oceans)[31], the European Maritime and Fisheries Fund (EMFF)[32], Copernicus Marine Environment Monitoring Service[33] and other programmes. Examples of these projects include the Horizon 2020 project "Seas, Oceans and Public Health in Europe" (SOPHIE, Box 1.1)[34] on oceans and human health, the Horizon 2020 project ClimeFish[35] on the impact of climate change on fisheries, and JPI Oceans funded projects on the impact of deep-sea mining[36], among many others. Ocean observation in Europe has been progressed by the European Ocean Observing System (EOOS)[37] initiative (Box 1.2), which is Europe's contribution to the IOC-UNESCO Global Ocean Observing System (GOOS). This initiative has put forward a strategy to coordinate ocean observations in Europe, with an implementation plan from 2018 to 2022.

The Navigating the Future series have therefore recommended many new and innovative research areas and has also made recommendations that have yet to be addressed and which are still valid. Marine science has continued to progress with new theories, ideas and methodologies and the European Marine Board thus found it timely to revisit the question of marine solutions to serve society. The development of Navigating the Future V was launched at a kick-off meeting in Brussels on 8–9th November 2017 (Annex 1). Nineteen experts from across Europe participated in the meeting with the aim of identifying novel marine solutions that serve society and ensuring that the outputs of Navigating the Future V translate into actions and raise the visibility of the ocean as a vital component of the Earth. The brief was to describe the future direction of marine science up to 2030, taking a holistic approach to ocean science and the solutions needed for the ocean. Over the two days of the meeting, the experts distilled five key scientific topics that are described in the next 5 chapters:

- The four-dimensional (4D) ocean;
- The impact of multiple and cumulative human stressors;
- The science of surprises – predicting extreme events and natural hazards;
- Ocean technologies, modelling and artificial intelligence advances needed for the ocean of tomorrow; and
- Fostering sustainability science.

Credit: European Marine Board

Experts brainstorm at Navigating the Future kick-off, Brussels, November 2017

30 https://ec.europa.eu/programmes/horizon2020/en
31 http://www.jpi-oceans.eu/
32 https://ec.europa.eu/fisheries/cfp/emff_en
33 http://marine.copernicus.eu/
34 https://sophie2020.eu/
35 https://climefish.eu/
36 http://www.jpi-oceans.eu/ecological-aspects-deep-sea-mining
37 http://www.eoos-ocean.eu/

2
A four-dimensional and connected ocean

Credit: NASA

The ocean is an interconnected three-dimensional volume where physical, geological, biogeochemical and biological characteristics change and interact. Time is therefore a highly relevant fourth dimension that compliments dynamic three-dimensional approaches. Active geological processes such as seafloor spreading at oceanic ridges and the convergence of plates at subduction and plate collisional zones shape our continents and influence the physical, biogeochemical and biological ocean. For example, they modify the chemistry of the ocean through active fluid release, fuel deep ocean chemosynthetic communities, form deep-sea mineral resources and are responsible for some of the largest and most destructive earthquakes, submarine landslides and tsunamis ever recorded (see Chapter 4.1.3 for more information on dynamic seafloor processes). In this chapter, we cover the changing physical, biochemical and biological aspects of the four-dimensional (4D) ocean and its management.

2.1. The physical ocean

The Arctic, Atlantic, Indian, Pacific and Southern Oceans are all interconnected as a single Global Ocean. The coupling of high salinity and low temperature increases the density of seawater and causes it to sink in a phenomenon called deep-water formation, which has a crucial role in the functioning of the world ocean. The formation of deep-water generates currents that connect all planetary waters into a single grand conveyor system or "Meridional Overturning Circulation" (MOC) (Figure 2.1).

This circulation transports huge quantities of heat, salt, oxygen, carbon dioxide (CO_2) and nutrients between the equator and the poles and drives the regional patterns of ocean temperature and acidification as well as the climate of the planet (Perez *et al.,* 2018). Dense water circulates globally and upwells, driven by winds and by mixing. The upper limbs (in purple, Fig. 2.1) of the conveyor return poleward as warm currents such as the Gulf Stream, which brings heat to Western Europe. Global change, and global warming in particular, alters this global ocean circulation. The melting of polar ice due to global warming produces low salinity waters that prevent sinking and the formation of deepwater thus impairing the functioning of the ocean conveyor system. The full impact of these changes in the physical ocean is not fully understood.

The ocean is and always has been a key player in past and ongoing climate change. Decadal-scale variability in ocean circulation impacts the global mean surface temperature and generates temporal fluctuations in the rate of global warming. On one hand, the ocean attenuates the effect of CO_2 emissions from land-based activities by absorbing heat and CO_2, but on the other hand, the ocean provides these services at the expense of the sustainability of its ecosystems, which are vulnerable to warming and acidification, reducing its capacity to attenuate global change.

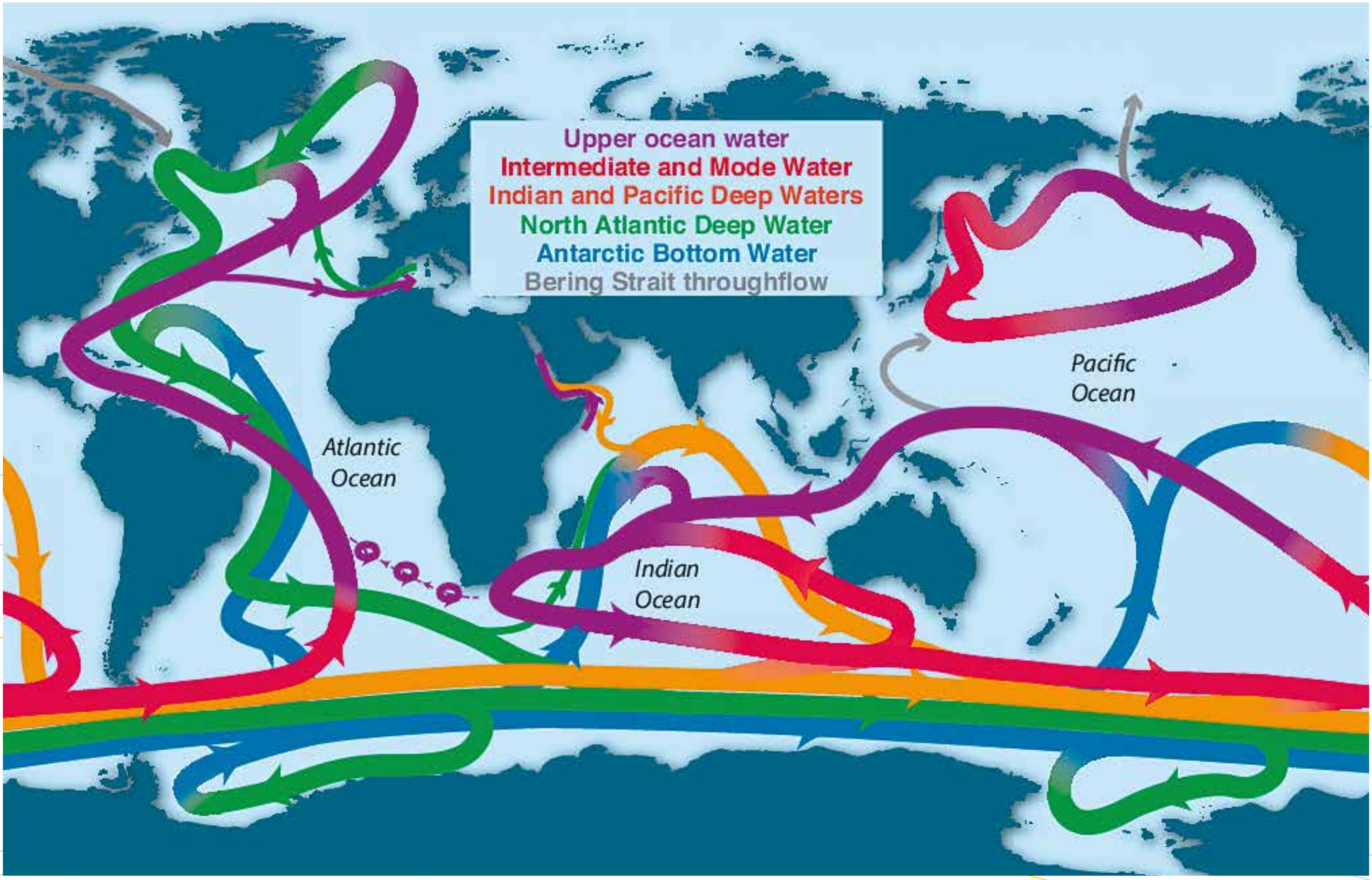


Figure 2.1 Global overturning circulation, driven by changes in wind, temperature and salinity. Adapted from Talley, 2015.

Water exchange through straits and transport between basins also plays a significant role in the short- and long-term modulation of climate in each ocean basin, as well as the coupling between them. Modifications of the water flow through these straits can result in changes in thermohaline circulation (Figure 2.1), which feeds back to global change. Inter-basin exchanges depend on wind as well as density contrasts. In some cases, these exchanges are caused by propagating eddies such as the Agulhas rings between the Indian and Atlantic Oceans. The modifications of these exchanges under climate change will thus result in increased complexity of coupling and feedback between ocean, atmosphere and sea ice.

The theory is that ocean surface warming implies a more stratified, less productive, and less oxygenated ocean. A more stratified ocean is predicted by several large-scale modelling studies (Schmidtko *et al.,* 2017). However, ocean models do not reproduce the seasonal cycle of mixed layer depths or the thickness of the mixed layer accurately (Sallée *et al.,* 2013). In some regions observations do not show any change in mixed layer depth with rising temperatures (Somavilla *et al.,* 2017). Therefore, long-term observations are needed to understand the difference between the observations and large-scale model predictions. For the North-West European shelf seas, models suggest that a warmer climate will advance the onset of spring stratification by a few days and postpone the seasonal breakdown of stratification by 5 – 10 days (MCCIP, 2010). In both cases, the causal factor is the increase in air temperature, which promotes stratification.

Changes in the hydrological cycle due to global warming cause changes in salinity (Byrne *et al.,* 2017). The effect of changes in salinity on stratification, including the indirect effects of increased freshwater runoff due to changing rainfall patterns, are considerably less well understood than the effect of warming. Regional predictions of wind and rainfall patterns from climate models have not been fully integrated with models of shelf-sea circulation so there are opportunities to better understand freshwater-driven stratification over all timescales.

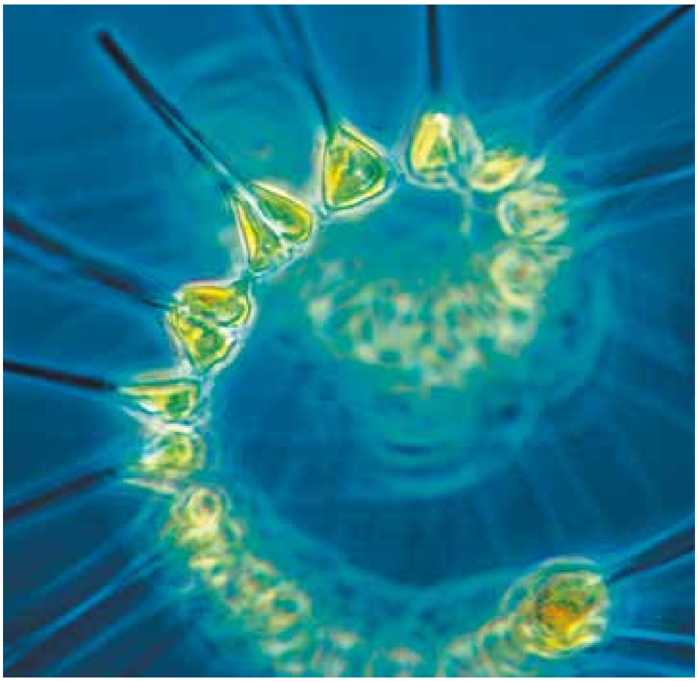
Water exchange through straits plays a significant role in the modulation of climate in ocean basins through alterations in water flow and subsequent changes in thermohaline circulation. The Bosphorus Strait in Turkey is shown here, captured by the Copernicus Sentinel-1 mission.

Continental drift and hydrodynamic patterns underpin the interconnectedness of the ocean and have a significant impact on marine organisms. They form populations and communities (i.e. biodiversity) that interact with the physical environment to form complex ecosystems that are dynamic and respond to both natural and anthropogenic environmental changes. For instance, straits and man-made waterways connect ocean basins for both invasive species and a number of economically important migratory fish species, ultimately directly impacting biodiversity in the basins they connect. Along with other physical and biological drivers, these large-scale water movements shape the structure and function of the world's marine ecosystems.

2.2. The biogeochemical ocean

Climate change affects many oceanic biogeochemical processes including oxygen production, carbon sequestration, nutrient exchange and ocean acidification. Direct and indirect changes to the temperature and density structure of the ocean influence ocean stratification, which plays a key role in many ocean biogeochemical processes. In particular, the mixed layer depth regulates light availability for photosynthesis and nutrient exchange from the deep to the upper oceans. Increased stratification, especially at high latitudes, leads to a reduced exchange of the upper layer of the ocean with deep waters affecting nutrient cycles and the reoxygenation of water. Any stratification-related changes to ocean ecosystems could result in irreversible changes to phytoplankton communities. This could feed back to alterations in oxygen production and carbon sequestration and could cause regime changes in marine food webs.

Oceanic oxygen supports the largest ecosystems on the planet (Figure 2.2). However, the ocean is losing oxygen, primarily due to global warming, and nutrient and organic waste pollution in coastal waters. Over the past 50 years, the volume of oxygen-depleted waters has expanded fourfold. Oxygen minimum zones have extended, and the oxygen concentration has decreased globally by approximately 1.5% since 1970 (Breitburg *et al.,* 2018). This loss of oxygen is a rapidly increasing threat to marine life and to coastal communities. Global warming impacts ocean oxygen in two ways: firstly, warmer water has reduced capacity to hold oxygen and, secondly, the reduction of ocean mixing and circulation limits the uptake of oxygen from the atmosphere, because when water is not mixed the top layer will be saturated with oxygen, while the bottom becomes anoxic. Deoxygenation disrupts marine ecosystems causing loss of habitats and biodiversity, which can have knock-on effects such as harming natural fish stocks and aquaculture. Deoxygenation is predicted to worsen in the coming years due to increasing nutrient input to coastal regions as human populations and economies grow and under continued global warming. Global warming can be accelerated by deoxygenation as this enhances marine production of greenhouse gases under low oxygen conditions, e.g. nitrous oxide (N_20, Babbin et al., 2015).



Phytoplankton are the foundations on which marine ecosystems are built. They are influenced by changes in ocean stratification, which could lead to altered oxygen production and carbon sequestration.

Since the beginning of the Industrial Revolution 250 years ago, ocean acidity has increased by 30%. Model projections have shown that, at the present rate of CO_2 emissions, the acidity of the ocean surface could triple by 2100. There are some studies on the impact that ocean acidification has on food chains and biodiversity, but more efforts are required to strengthen our knowledge about the impact of acidification on the wider food web.

Carbon sequestration through the marine biological food web and the effects on marine ecosystems are difficult to predict. The activity of the biological pump is strongly regulated by net primary production and an important research area is to consider the effects of climate change on photosynthesis as well as its positive feedback on climate change through carbon sequestration. For more on changes in the physical and chemical ocean see Chapter 3.

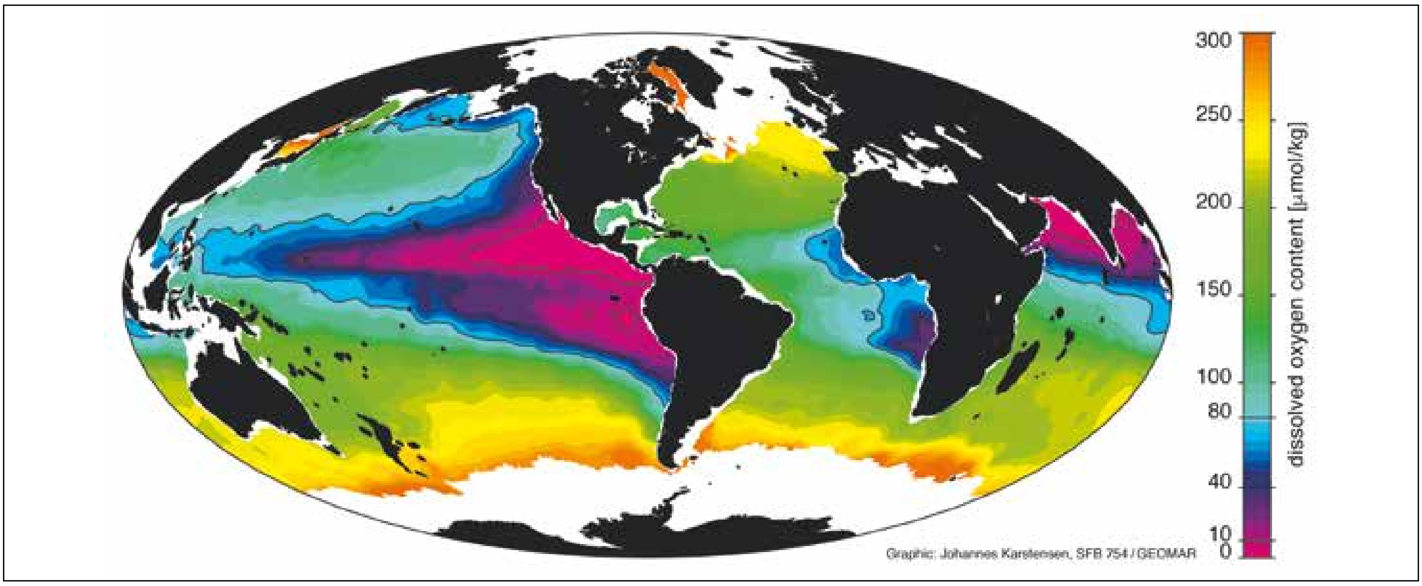


Figure 2.2. Distribution of oxygen at 300–500m water depth from well ventilated (yellow) to very poorly ventilated areas (purple).

2.3. The biological ocean

Marine biodiversity is often characterized as plankton (organisms that live in suspension in the water column with limited mobility), benthos (organisms that live within or on the sea floor), and nekton (animals that live in the water column that can actively swim). However, ocean life is in reality far more complex. Most living phyla have marine representatives, with sizes that range from the smallest (viruses) to the largest living beings (the blue whale). They play different roles throughout their life, inhabiting different environments and providing different functions. To understand the role of species in the 4D ocean and how they are affected by its changes, we must understand their life cycles and their place in the marine food web. Most of the known marine species have life cycles that are not yet fully described. The trophic relationships (who eats whom) between these life stages are often also unknown, especially for species that have no immediate economic value. To understand how the ecosystem services provided by marine biodiversity will change (Worm *et al.,* 2006) we must first understand how these services are linked to the species that provide them, through both trophic food webs and non-trophic pathways i.e. lifecycles or biogeochemical pathways (Boero *et al.,* 2019).

Marine systems are in a constant state of change driven by processes that take place in the water column and on the sea floor. The primary producers (i.e. nutrient-driven photosynthetic or chemosynthetic species) of marine ecosystems primarily consist of microalgae that live suspended in the water (phytoplankton). Shallow coastal systems are additionally fuelled by other primary producers, such as benthic microalgae, macroalgae, seagrasses and mangroves. Primary production is at the base of the marine food web, sustaining most biota directly or indirectly. Phytoplankton live in the euphotic zone, where light enables photosynthesis, but the organic material they produce sinks through the volume of the ocean where it is used by plankton (including viruses and bacteria) and benthos, and fuels the nekton. Therefore, the processes that take place in the upper water column are at the core of the functioning of most marine life and have a great bearing on all biodiversity and ecosystem functions, including those on the deepest ocean floor. Chemosynthetic animals associated with hydrothermal vents in the deep sea create a completely different food web that depends not on photosynthesis in the euphotic zone, but on converting chemicals expelled from the Earth's crust into energy.

The interactions between the components of marine systems represent a complex and dynamic network. Changes in the physical environment and the industrial removal of fish and other species disrupts the network by removing top predators and even mid-level species and leading to trophic downgrading, i.e. the simplification of food webs via the disappearance of high

Credit: Sheila Heymans

Seastars on Broken Islands, Canada. To understand the role of species in the 4D ocean and how they are affected by its changes, we must understand their life cycles and their place in the marine food web.

trophic levels (Britten *et al.,* 2014). To understand the effect of these human impacts on marine ecosystems, or networks, and to adopt appropriate science-based management and conservation measures to protect them means knowledge of these patterns and processes is needed.

The bottom-up drivers of change in marine ecosystems, such as the influence of light and nutrient availability on phytoplankton production, are relatively well understood. However, further research is needed on top-down processes, such as the impact of zooplankton grazing on phytoplankton, fish grazing on zooplankton, and top predators feeding on both fish and plankton. In addition, the interplay of life-cycle patterns (e.g. the transition to plankton resting stage to sediments), the seasonal and inter-annual variability in production, and the mixed impacts of top-down and bottom-up processes are only partially understood for most of the world's oceans. Similarly, the competition between primary producers for light and nutrients is not well known. The mix between different trophic pathways, i.e. sub-webs of ocean food webs, and how these respond to different stressors is also incompletely understood. To untangle these processes, we still need to study the "natural history" of marine species. For instance, the rapid turnover of phytoplankton is due to the interplay of species-specific life-cycle features and the fine-scale processes that control phytoplankton blooms, coupling biogeochemistry, life history processes and food web dynamics. These processes are not well understood, including the capacity of some groups to switch between primary production and grazing – known as mixotrophy – which might be one of the most common means of fuelling open ocean expanses (Stoecker *et al.,* 2017).

Microbes are important organisms in oceanic food webs. The microbial loop is a crucial component of marine ecosystems allowing dissolved organic carbon (a resource most marine organisms are not able to utilize) to be incorporated into microbial biomass and subsequently transferred to higher trophic levels. This contributes to the productivity of the ocean and seas by enhancing primary production and decomposition. However, the interplay between the microbial loop and the rest of the planktonic food web needs further research.

The distribution of biodiversity and ecosystems, formed through interaction with the physical world, is not homogenous. Ecosystem processes based on connectivity can drive the variation in distribution patterns of biodiversity. Thus, apparently distant areas of the marine realm can depend on each other through processes that occur at various scales.

2.4. Managing change in the four-dimensional ocean

The connectivity linking populations of marine species into meta-populations could be used to identify highly connected systems in volumes (not areas) for management and conservation. Connectivity is critical, for example propagules (i.e. life stages that move in the water) can exchange across meta-populations and propagules are also components of food webs, being consumed by

Credit: Mert Gokalp

Industrial removal of fish removes top predators and mid-level species leading to tropic downgrading.

predators in other parts of the ecosystem. Current management and conservation approaches are mostly based on the areas where the main (adult) population occurs, and does not always include the areas where the species spawn, where the larvae drift, or where their main food sources live.

Similarly, many marine protected areas (MPAs) protect the species settled in that area but do not take into account the connections of the resident biota to the rest of the ecosystem. This lack of coverage of crucial parts of the life cycle of species, due to limited understanding of the functioning of marine ecosystems, leads to ineffectual management of natural resources in terms of both sustainable exploitation and protection. Given that the ocean spans 99% of the volume of the habitable space on the planet for species but covers "only" 71% of the planet's surface, we should probably focus more on managing the ocean on a volumetric rather than areal basis. Management should always include the coherent spatial units that comprise the full 4D ocean to include patterns of biodiversity distribution and processes of ecosystem function. **We should be thinking of marine protected volumes (MPVs), instead of marine protected areas.**

Credit: Nicolas Bailly

Marine conservation suggests the misleading expectation of "conserving" the ocean, conveying the message that things must remain stable.

Integrated Ecosystem Assessment, or IEA, is a framework used to organize science to inform decision-making in marine ecosystem-based management at multiple scales and across sectors, representing a more holistic approach to managing ecosystems. IEA has been implemented in both Europe and North America (Link & Browman, 2017). However, to have a truly holistic approach that merges physics, chemistry, geology, biology, ecology and socio-economics, we should manage marine ecosystems in Cells of Ecosystem Functioning (CEFs). CEFs are the smallest fully connected portions (i.e. volumes) of the marine environment, where biodiversity patterns and ecosystem functions depend on each other (Boero *et al.,* 2019). Together, CEFs make up Large Marine Ecosystems (LMEs)[38], which are larger regions of ecological unity that have been used for fisheries management internationally. CEFs do not correspond to the usually considered domains of the oceans (i.e. plankton, nekton, benthos, coastal, high seas, deep sea) and biogeographic zones, but host coherent biodiversity distribution patterns depending on, and generating, coherent ecosystem functions. Connectivity occurs within species (by dispersal) and across species (through food web and habitat mediated links) and is assessed by considering both biodiversity (species) and ecosystem functioning (food webs). This holistic approach is conducive to a full understanding of how marine ecosystems are formed and how they function, identifying the most important connections that link components that, so far, have typically been kept separate for ease of analysis.

Marine conservation suggests the misleading expectation of "conserving" the ocean, conveying the message that things must remain stable. In ecology, where change is normal, the "ecological equilibrium" argument is invoked whenever the necessity of preserving nature is advocated. However, the ocean is not a stable habitat, even over relatively short time periods. Marine benthic systems (e.g. seagrass meadows, coral reefs) show some longevity in their ecological stability, but this does not apply to the water column, where plankton and nekton are highly dynamic and ecosystems often function in pulses, going through continuous change.

The stability principle is invoked in the first descriptor of Good Environmental Status (GES)[39] in the EU's Marine Strategy Framework Directive (MSFD), which requires that "Biodiversity is maintained". However, the strict maintenance of biodiversity can only be evaluated by specialized experts (i.e. taxonomists and ecologists) and it should not be based on a benchmark situation that cannot change, since change is the benchmark of evolving biological systems. GES also does not take into consideration the impact that climate change might have on species, with species moving poleward or deeper to maintain their optimal thermal range.

[38] http://www.lmehub.net/

[39] http://ec.europa.eu/environment/marine/good-environmental-status/index_en.htm

Kelp washes up on beaches due to storm action and natural processes providing nutrients to the beach environment. Beach cleaning in tourist areas removes these nutrients.

Nor does it take into account the natural turnover of species that is the hallmark of life on Earth. None of these considerations can be addressed through short-term management. Moreover, all GES descriptors should be applied at the same time, since environmental impacts can have a wide range of effects on different parts of the ecosystem, sometimes acting in synergy (multiple stressors, see Chapter 3). Understanding GES links biodiversity to ecosystem functioning and calls for thorough knowledge and understanding of the structure and function of marine systems, which in turn requires full appreciation of the processes that maintain healthy ecosystems and biodiversity.

Framing ecological processes in space, through the definition of CEFs, is necessary but not sufficient since the connections that determine the CEFs are constantly changing over time driven by natural and anthropogenic variation. To account for these changes, long-term sustained observation systems are needed which focus on biodiversity and ecosystem functioning over time, and supplement the existing observatories that focus on physics and biogeochemistry.

The knowledge of the role of evolution in biodiversity and ecosystem functioning at biological timescales is crucial to design management options that recognize adaptation to continuously changing natural conditions. This allows us to adjust and adapt our activities to the evolution of the ecological systems that sustain us, while attempting to reduce our impacts to increase our well-being and prosperity through sustainable ways of life. Understanding the history (i.e. change) of a system is conducive to better management and protection. In this sense, the study of the past evolution of marine life and mass extinctions within a paleoceanographic context, recorded in the ocean sediments, allows extension of our present day perspective into a wider 4D scenario at multiple temporal and spatial scales. This allows separation of long-term global change by natural processes from anthropogenic induced change.

2.5. Conclusion and recommendations

The ocean is an interconnected 3D volume that changes over time, which represents a highly relevant fourth dimension. A change in focus from areas to volumes and the realization that stability and equilibrium are not suitable concepts for marine systems are needed. This requires the merging of approaches that, so far, have developed in isolation.

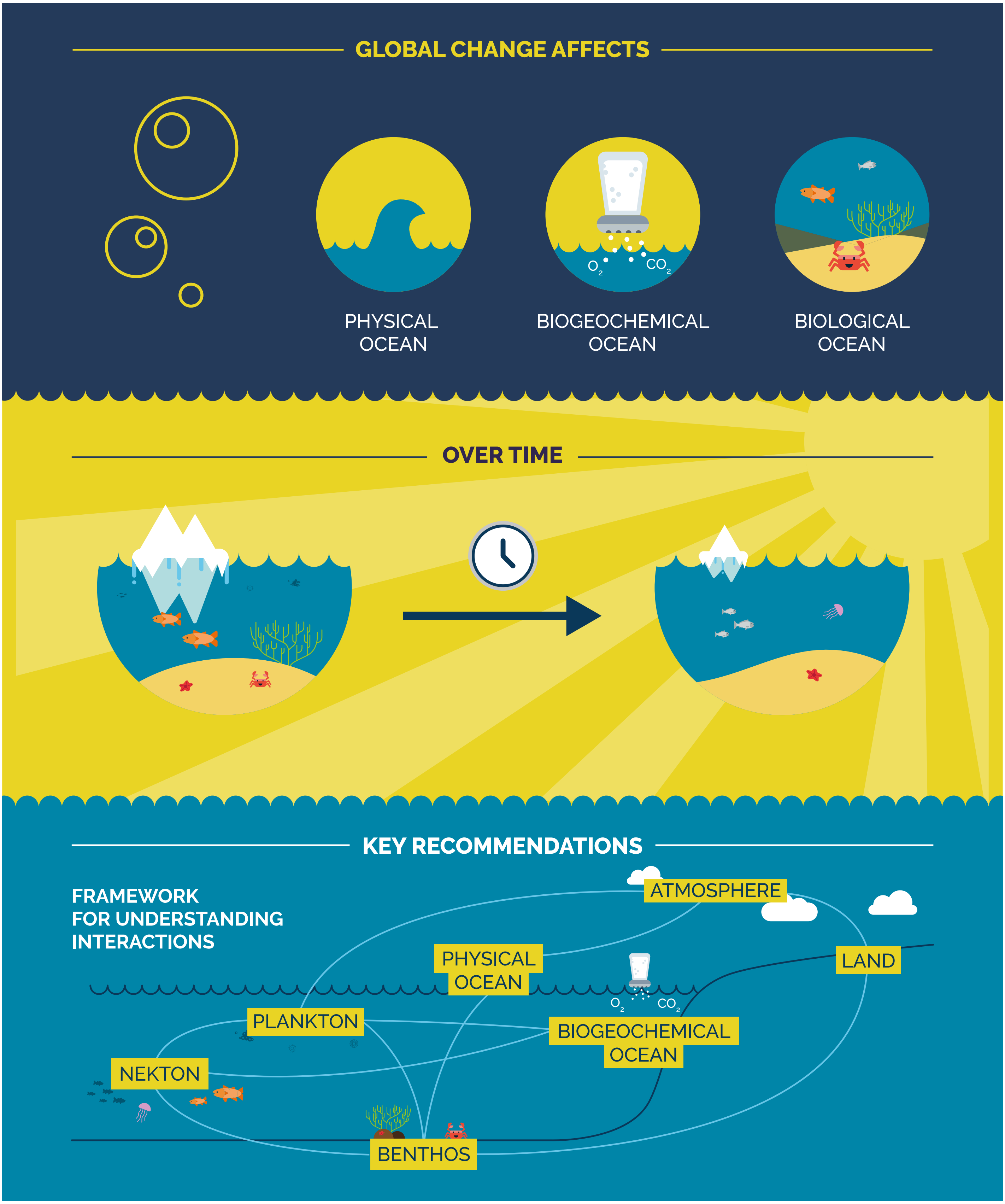
The biogeochemical explanation of plankton pulses driving marine ecosystem functioning must be joined with explanations based on life-cycle patterns and food web processes that link plankton, benthos, nekton and humans into a single grand picture of marine systems based on connectivity. In addition, the impacts that feedback loops have on ecosystems also need to be incorporated. Integrated management systems such as Integrated Ecosystem Assessments (IEAs) and concepts such as Cells of Ecosystem Functioning (CEFs) are needed to sustainably manage ecosystems. However, it should be recognized that ecosystems will change in response to changes in climate and subsequently have a bearing on climate itself.

The most important priority for understanding the 4D ocean is to establish an interdisciplinary programme on ocean connectivity that would help to:

- Understand the impact of active geodynamic processes on changes in ocean chemistry, sustaining deep marine ecosystems and hazards;
- Understand the influence of climate change on the physico-chemical characteristics of the connected ocean;
- Understand the effects of physical processes such as eddies on the connectivity of marine ecosystems;
- Understand the impact of temperature change and ocean acidification on the larger food web;
- Identify functional links that connect marine ecosystems and a spatial framework for biodiversity patterns and ecosystem processes e.g. Cells of Ecosystem Functioning (CEFs);
- Set up observing systems for biodiversity and ecosystem functioning to supplement biogeochemical and physical observations; and
- Integrate the structure and function of marine ecosystems and their evolution over time into management and conservation practices.

Credit: Nicolas Bailly

Moray Eel. Distant areas of the marine realm can depend on each other through processes that occur at various scales.


GLOBAL CHANGE AFFECTS
PHYSICAL OCEAN
O_2
CO_2
BIOGEOCHEMICAL OCEAN
BIOLOGICAL OCEAN
OVER TIME
KEY RECOMMENDATIONS
FRAMEWORK FOR UNDERSTANDING INTERACTIONS
ATMOSPHERE
LAND
PHYSICAL OCEAN
O_2
CO_2
PLANKTON
BIOGEOCHEMICAL OCEAN
NEKTON
BENTHOS

3
A multi-stressed and rapidly changing ocean

Microplastics at Ostend beach. Credit: VLIZ

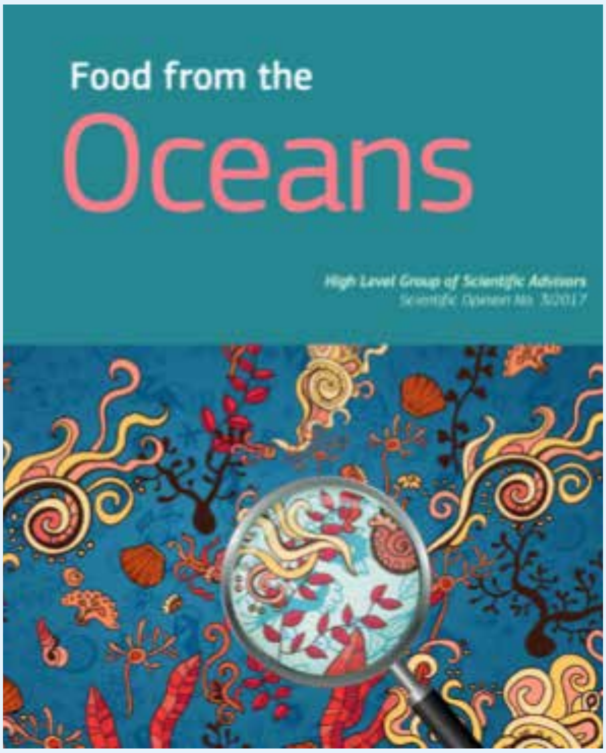


Credit: Gerald Schernewski

The ocean is increasingly exposed to multiple drivers[40] of environmental change, which include many different stressors. Global change affects temperature, salinity and ocean currents, also causing decreased oxygen levels and increased stratification and ocean acidification. Human activities affect the ocean and include population growth, consumption, energy use and land-use changes. These result in physical stressors, such as habitat loss or alteration, noise, light, erosion, sedimentation, litter and chemical stressors, such as (persistent) organic pollutants, metals and eutrophication. Human activities impacting the ocean have increased and overlapped, especially in coastal and shelf areas – the most productive and used areas of the seas (Ramírez *et al.,* 2018). Human activities will continue to increase under the European Commission's Blue Growth agenda[41] and the increased need for food from the oceans (Scientific Advice Mechanism (SAM), 2017), Box 3.1), and will probably increase biological stressors such as invasive species, parasites, pathogenic bacteria and viruses. Single stressor effects are not fully understood for emerging pollutants like micro- and nanoplastics (Box 3.3), pharmaceuticals and biocides. **Many stressors act concurrently and their impacts cannot be assessed without considering their cumulative effects and interactions.**

BOX 3.1. FOOD FROM THE OCEANS

The 'Food from the Oceans' report (Scientific Advice Mechanism (SAM), 2017) highlights the need for living resources from the ocean to feed the growing world population. Until recently, most food from the oceans came from harvesting wild populations, but the growth of wild harvest has plateaued and in the future aquaculture will be very important. However, the impact of increased aquaculture is not insignificant. Although some aquaculture species are filter feeders (e.g. bivalves such as oysters and mussels) or herbivorous fish (e.g. tilapia), many are carnivorous and require fishmeal and fish oil, which often comes from wild fisheries, such as the anchovy fisheries off Peru. The sustainability of the culture of carnivorous species is in question and may not represent a long-term solution, potentially exacerbating the problem of overfishing. Therefore, alternative solutions have to be explored, such as shifting to lower trophic level species in both wild fisheries and aquaculture, new sources of proteins and oil for fish feed, and increased land-based freshwater aquaculture. Research is therefore needed to investigate new species for aquaculture, new methods of aquaculture, feed production technologies, food quality and safety, biotechnology, fishing policies, social acceptance of aquaculture species as well as ecosystem functioning and the potential harvesting of little utilized resources near the base of the food web. In addition, research on life-cycle analysis, reducing waste, and waste handling is critical.



[40] A "Driver" is a pressure that drives an ecosystem and is a more universal term than "stressor", as some drivers may result in positive effects thus not necessarily stressing the system. Drivers are usually related to a specific ecosystem and largely affect the dynamics of that ecosystem.

[41] https://ec.europa.eu/maritimeaffairs/policy/blue_growth_en

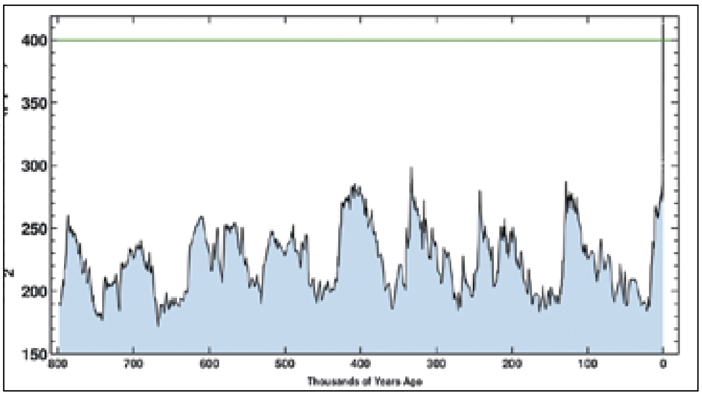
3.1. Changes in ocean drivers

There have been significant changes recorded in the Earth system throughout its history. However, the ongoing anthropogenic changes are unprecedented. The CO_2 concentration in the atmosphere is higher now than for the past 800,000 years (Figure 3.1), and is the cause of ocean warming and acidification. Future climate change depends on future greenhouse gas emissions, which in turn depend on international policy (Figure 3.2). Scenarios compatible with the Paris agreement (limiting warming to 2°C or 1.5°C) require a drastic decline of emissions starting in 2020 or 2030 (red and blue curves in Figure 3.2).

As warming, sea-level rise and acidification have become more pronounced over the last century, the impacts on our ocean are becoming more evident (IPCC, 2014). There are a number of other overarching global stressors (or drivers) which exert a major influence on the scope and scale of these impacts. These include a significant increase in the world's population (7.5 billion in 2017 having doubled since 1972, (UNCTAD, 2018), Figure 3.3), with coastal areas facing increasing urbanization and resource utilization as a consequence of a disproportionate population growth (Neumann *et al.,* 2015). Additionally, consumerism and international trade are growing, with associated increases in atmospheric emissions of greenhouse gases and global marine pollution. In addition to increasing pressure from population growth, there are also impacts from climate change on many drivers of ocean processes (Box 3.4 and 3.5). The consequences of the ocean storing extra heat (IPCC, 2013) include increasing ocean temperatures and sea-level rise through expansion of the water column. Atmospheric warming causes melting of terrestrial ice shelves and sheets, which also contributes to rising sea levels and as a result of these changes the global mean sea level has increased by 75 mm since 1993 (Nerem *et al.,* 2018). Thus, global drivers have impacts, which themselves are stressors. For example, alterations to pH, temperature, irradiance, nutrients, oxygen and an increase in sea level all result in stressors on the biology of the ocean (Boyd *et al.,* 2018).

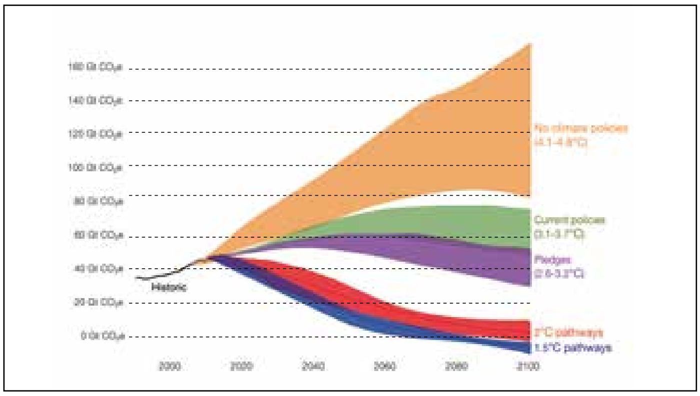
The difficulty is that the ocean is a dynamic, non-linear and rapidly changing system. This creates complexities in determining impacts from multiple sources over time. There are also complexities when considering the interaction of impacts and their differences at temporal and spatial scales. These may all vary in different regions of the world.

An example of multiple stressors is the compression of species into smaller volumes through climate change induced hypoxia. Longshore winds in spring and summer induced by climate change intensify offshore advection and upwelling, which could lead to more frequent hypoxia events (Bakun *et al.,* 2015) and the arrival of species that spend part of their life cycle in deep water, such as jellyfish (Benedetti-Cecchi *et al.,* 2015). Benthic organisms found in regions where a low oxygen layer intersects the continental margin could be directly impacted, while pelagic species could find their viable habitats compressed. The biological impacts of anoxic events can be catastrophic, with widespread mortality of macroscopic benthic organisms, resulting in periodic dead zones (Bakun *et al.,* 2015). This reduction in habitat increases exposure to human activities such as fishing.



Credit: Scripps Institution of Oceanography

Figure 3.1. CO_2 concentration from Mauna Loa (Hawaii) from 1958 to present, placed in the context of ice core data from 800,000 years ago to present (Lüthi *et al.*, 2008). The concentration reached 400 parts per million (ppm) in 2013, a value never encountered in the past 800,000 years.



Credit: Our World in Data[42]

Figure 3.2. Global greenhouse gas emission scenarios based on data from the Climate Action Tracker (CAT). Emissions measured in gigatonnes of CO_2 equivalents. Temperature figures represent the estimated average global temperature increase from pre-industrial levels by 2100.
Licensed under CC-BY-SA by Hannah Ritchie and Max Roser.

[42] https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

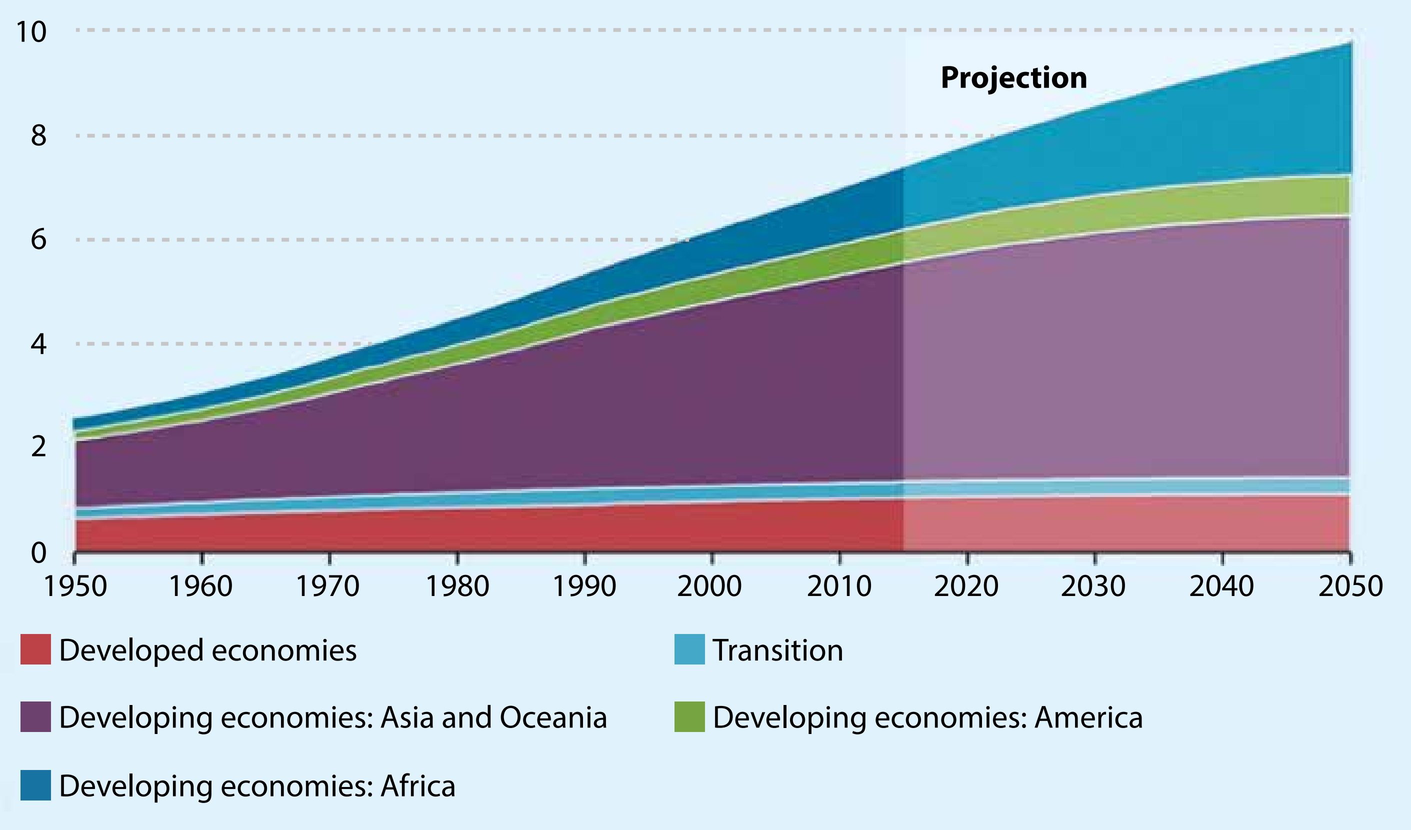


Figure 3.3. World population (billions) between 1950 and 2050 by group of economies (UNCTAD, 2018)

3.2. Impacts of change

The European blue economy represented €174 billion of added value in 2016 and the ocean economy may double its contribution to global added value between 2010 and 2030 (European Commission, 2018; OECD, 2016). With an increasing world population turning more towards the ocean to provide necessary resources, an increased exposure of the ocean to multiple stressors can be expected. At the same time, the UN Sustainable Development Goals (SDGs) clearly aim to protect and sustainably use the ocean, seas and marine resources, as most SDGs link with the ocean (Le Blanc *et al.*, 2017). Hence, the ocean as part of the larger Earth system should remain in a safe operating space (Rockström *et al.*, 2009). To understand the impact of these global drivers we will need to move beyond concepts of multidisciplinary approaches to transdisciplinary research (Box 3.2), experiments and models.

The assessment of the impacts of multiple and cumulative ocean stressors is a continuing challenge. **Effects of single stressors or binary combinations of stressors are often studied, but there is no one uniform framework for evaluating the cumulative and often interactive impacts of multiple stressors.** (Boyd *et al.*, 2018).

BOX 3.2. MULTIDISCIPLINARITY, INTERDISCIPLINARITY AND TRANSDISCIPLINARITY

Multidisciplinarity combines disciplinary perspectives in an additive manner providing their viewpoint on a problem from each of their perspectives. Multidisciplinarity involves little interaction across disciplines.

Interdisciplinarity combines two or more disciplines to a new level of integration suggesting component boundaries start to break down. There is a recognition that each discipline can affect the research output of the other.

Transdisciplinarity occurs when two or more disciplines transcend each other to form a new holistic approach. The outcome will be completely different from what one would expect from the addition of the parts.

An example is in the context of cumulative effects assessments (Stelzenmüller *et al.,* 2018). The sensitivities of species to multiple stressors are often determined based on expert judgement, limiting knowledge of the size of the effect and usually not acknowledging the uncertainty in the estimations.

There are large knowledge gaps on the interactive effects of multiple drivers of change on different components of marine ecosystems. These effects may be additive or multiplicative, and each may either aggravate or mitigate the direction of responses. Non-additive responses exhibit interactions between the effects of multiple stressors and are often complex and likely to be important in marine ecosystems, as demonstrated in studies of binary stressor combinations (e.g. Villar-Argaiz *et al.,* 2018). The temporal aspects of short-lived versus continuous stressors, which may cause accumulated effects, should be taken into account. Another area of research that needs to be further developed is how multiple stressors affect evolutionary responses to key drivers such as climate change and the adaptation of species to stressors over time. There may be an influence on the ability for recovery and the resilience of marine ecosystem components, which is fundamental to our capability to predict future oceans. The study of paleoceanography and the investigation of the effects of past major climate change on global biodiversity extinction/adaptation can also provide useful complementary insight into these processes.

Many drivers or stressors have a linear relationship with their resulting impacts, potentially leading to tipping points when ecosystem thresholds are surpassed. Around these tipping points, large ecological responses result from relatively small changes in a driver (Selkoe *et al.,* 2015). The impact of stressors is often estimated based on linear relationships, ignoring tipping points and their important ecological consequences. However, an extensive literature review found that more than 52% of the driver–response relationships in pelagic ecosystems are non-linear (Hunsicker *et al.,* 2015). Tipping points are further discussed in Chapter 4.

BOX 3.3. ADDRESSING PLASTIC POLLUTION

Plastic debris is a material of high societal concern and has been declared an unnatural stressor for a wide range of organisms, an eyesore and an unethical addition to nature (SAPEA, 2019). It is estimated that 8.3 billion metric tons of new plastics have been produced worldwide since 1950. The durability and resistance to degradation of plastics makes them versatile for innumerable applications but also makes it difficult or impossible for nature to assimilate them (Geyer *et al.,* 2017). Microplastics are defined as plastic debris particles smaller than 5 mm (including those in the nano size range: 0.1µm to <1µm) (GESAMP & Kershaw, 2015). They have been detected in air, soils, freshwater, drinking water, the ocean and in food products such as seafood and table salt (SAPEA, 2019). Micro- and nanoplastics are directly introduced into the environment; for example, when using cosmetic products (although many cosmetic producers now avoid using microplastics) and from washing clothing. Environmental factors act on large pieces of plastic debris, which break down into smaller sized debris. This is among the most common source of micro- and nanoplastic pollution.

As micro- and nanoplastics have only recently become an issue, the consequences of plastics in the marine environment are still mostly unknown. An increasing number of studies are being published allowing application of a common risk assessment approach (Everaert *et al.,* 2018). Recently, addressing plastic pollution has become a priority for governments (e.g. the European Union's Strategy for Plastics in a Circular Economy[43], the G7 Innovation Challenge to Address Marine Plastic Litter[44] and Ocean Plastics Charter[45], and the UN Environment Global Plastics Platform[46], among others). The private sector has also created initiatives to clean up plastics and prevent the introduction of more plastics into the environment, and there is increased societal awareness of plastic pollution[47].

Efforts are being made to standardize methods to quantify plastics in the environment and to understand the toxicological and ecological effects on marine organisms and ultimately on human health. This is through actions such as the Joint Programming Initiative (JPI) Healthy and Productive Seas and Oceans call 'Ecological aspects of microplastics in the marine environment'[48] and the development of detection and monitoring systems for remote detection of marine litter, such as the Scientific Committee on Oceanic Research (SCOR) Working Group on Floating Litter and its Oceanic TranSport Analysis and Modelling (FLOTSAM)[49].

Plastic pollution and its effects on the marine environment can also be used as a proxy for other problems such as marine pollution, ocean acidification or biodiversity loss. The marine science community must show the importance of marine research understanding and tackling the plastics problem and its economic impacts. For example, understanding ocean currents provides information on where plastic debris will accumulate. Ecotoxicological studies of marine species allow improved assessments of the environmental impact of plastic pollution and potential impacts on human health through seafood consumption are beginning to emerge (Smith *et al.,* 2018). In addition, investigating how plastic pollution interacts with other ocean stressors may allow marine science to be part of the conversation for mitigating, preventing and monitoring the impacts of plastic pollution in the environment.

[43] http://ec.europa.eu/environment/waste/plastic_waste.htm
[44] https://g7.gc.ca/en/g7-presidency/themes/working-together-climate-change-oceans-clean-energy/g7-ministerial-meeting/joint-chairs-summary/g7-innovation-challenge-address-marine-plastic-litter/
[45] https://g7.gc.ca/wp-content/uploads/2018/06/OceanPlasticsCharter.pdf
[46] https://www.unenvironment.org/news-and-stories/press-release/nations-commit-fight-plastic-pollution-together-during-un-general
[47] https://skyoceanrescue.com/
[48] http://www.jpi-oceans.eu/ecological-aspects-microplastics
[49] http://scor-flotsam.it/index.html

BOX 3.4. IMPACT OF CLIMATE CHANGE ON THE BIOSPHERE

The Mediterranean Sea is being colonized by hundreds of tropical species invading through the Suez Canal.

Species generally have an optimal range of temperature, salinity, light, etc. for maximal growth. Tropical biota cannot withstand temperature changes, neither lower nor higher than their range. For example, coral bleaching due to high temperatures is already affecting most coral reefs. Northern latitude species require much colder waters and climate change is leading to the deepening of the summer thermocline, which leads to mass mortalities of species that live below the previous thermocline depth.

Species "follow" optimal conditions and move where their limits of tolerance are satisfied. For instance, the Mediterranean Sea is being colonized by hundreds of tropical species invading through the Suez Canal. Temperate species will move North if possible, while polar species have no place to go. If species do not find a refuge from thermal stress, they will be driven towards extirpation (local extinction) and even global extinction. An example is the Northern Adriatic Sea, where stenothermic species, which are only capable of living within a narrow temperature range, cannot escape Northward or into deeper waters if temperatures increase further. Some of these species might already be locally extinct or suffer from temperatures that are too high. Even if the natural response to global warming is simply an adjustment of the biota to new conditions, the movement of species will lead to ecosystem change with unknown consequences for ecosystem services. In addition, biotic interactions will be disrupted (e.g. due to shifts in phenology and temperature-driven shrinkage of marine organisms), and entire ecosystems including their diversity (some of which is attached to the seabed) cannot simply shift poleward as a unified whole. Thus, climate change has a direct role in the loss of biological diversity, and this loss contributes in turn to the alteration of ecosystems. The examples given here are related to temperature changes but similar effects result from ocean acidification and deoxygenation.

In order to understand and forecast these potential impacts, new observations and modelling capacities are required. Large-scale research infrastructures, such as the Integrated Carbon Observation System[50], the European Multidisciplinary Seafloor and water column Observatory[51] and LifeWatch[52] and its European Infrastructure for Biodiversity and Ecosystem Research[53] will increase and automate ocean observations and yield long-term, uniform and "FAIR" (Findable, Accessible, Interoperable and Reusable, Wilkinson *et al.,* 2016) data. This data will in turn lead to better statistical and mechanistic models relating stressors to effects, which should be combined in multi-model ensembles, as proposed by Spence *et al.,* (2018) and advocated in the European Marine Board Future Science Brief N° 4 on ecosystem modelling (Heymans *et al.,* 2018). This approach can yield valuable insights into both the main drivers of change affecting ecosystem components and the determination of tipping points, which are useful for management decisions related to ecosystem service goals (Everaert *et al.,* 2018). Models and frameworks adapted from other scientific fields, such as microbial spoilage of food or ecotoxicology, can lead to better understanding of multiple modes of interaction between ocean stressors. Rapid developments in big data analyses, machine learning, artificial intelligence, and computing possibilities, combined with the evolution in molecular data generation and Earth observation capabilities, open new research avenues for modelling and evaluating multiple stress impacts on the ocean (Dafforn *et al.,* 2015). However, current observation systems do not provide all the relevant data since biological observations are not as prevalent as physical, geological and biogeochemical observations (Benedetti-Cecchi *et al.,* 2018). This lack of biological information must be addressed by upgrading current observing systems, which will lead to better models. Observations and models are further explored in Chapter 5.

50 https://www.icos-ri.eu/
51 http://emso.eu/
52 https://www.lifewatch.eu/
53 https://www.lifewatch.eu/web/guest/home

BOX 3.5. IMPACT OF CLIMATE CHANGE ON COASTS

The ocean drives climate: warmer oceans result in an increase in evaporation and in the strength of storm events such as hurricanes, with large impacts on biota, human activities and coastal protection. Sea-level change will affect coastal activities worldwide. Some oceanic islands are already being submerged and sea-level rise, linked with increased storminess, will increase coastal erosion. The challenge is to estimate the magnitude of these increases, with the regional disparities and associated uncertainties. These uncertainties derive from three major sources: the lack of fully understood climatic processes that affect sea-level change (e.g. the rate of ice flowing from the polar ice caps to the ocean), the uncertainty concerning future greenhouse gas emissions, and the effectiveness of adaptation and coastal protection measures. Coastal areas are zones of concentrated biodiversity and natural productivity and will be particularly affected by multiple stressors because this is where most human activities take place and where pressure accumulates due to the migration of humans to the seashore.

Credit: Sheila Heymans

3.3. Policy drivers

At the European level, governance of European coasts and the marine environment falls under the various jurisdictions of states and the EU. Within the EU, Member States have agreed a number of regulations and directives, which are directly applicable and which provide a legally binding framework for implementing legislation and action at national level. Some notable examples of legislative frameworks include the Water Framework Directive (2000/60/EC)[54], the Marine Strategy Framework Directive (2008/56/EC)[55], and the Maritime Spatial Planning Directive (2014/89/EU)[56], as well as a host of other legal and funding measures. **The ongoing challenge for science is to identify what scientific knowledge is required, for what purposes and at what time in order to provide the necessary scientific support to policymaking and implementation.**

The European Commission has identified a number of priority areas for research in the marine environment[57]:

- Processes and functioning of the marine environment;
- The functional role, evolution, protection and exploitation of marine biodiversity;
- The impact of human activities (land-based and marine) on coastal and marine ecosystems and how to manage these (including via eco-efficient technologies);
- How to apply an Ecosystem Approach to resource management and spatial planning to come up with the best options for coastal and maritime spatial planning;
- Deep-sea ecosystems, technologies to enhance deep-sea observation, sediments in continental margins and the deep sea, gas hydrate behaviour, etc.

[54] http://ec.europa.eu/environment/water/water-framework/index_en.html
[55] http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm
[56] https://ec.europa.eu/maritimeaffairs/publications/maritime-spatial-planning-directive_en
[57] http://ec.europa.eu/environment/marine/research/index_en.htm

Credit: Sheila Heymans

Offshore wind installation vessels in Ostend Harbour.

Finding answers to these and the many other topics linked to the ocean system, as well as human exploitation and use of the ocean, are critical to realizing the ambitious goals within the EU for the development of strong Blue Growth and a vibrant maritime economy. However, these goals need to be placed within two contrasting contexts.

First, changes to the marine environment are increasingly influenced by regional drivers such as human population growth and consumption, energy use, land-use changes and pollution, that manifest themselves at a global scale (e.g. climate change, acidification) (Camill, 2010). These drivers lead to local/regional responses (e.g. aquaculture, coastal protection measurements, erosion and sedimentation, invasion of species) that can further exacerbate the effects and rate of change at regional and global scales. It is important to understand how the consequences of current practices and activities will affect future options for sustainability based on global mechanisms that drive effects and rates of change as well as regional/local specific stressors and solutions (van Vuuren *et al.,* 2007).

Second, global drivers and the pressures they place on regional processes have to be reconciled with regional/national interests that focus on balancing sovereignty and security, natural hazards, energy and food security with global challenges that emphasize biodiversity conservation and ecosystem health, climate change and resource use and allocation (Jacquet *et al.,* 2011). Therefore, the issue of global versus regional and local challenges for marine research is based on reconciling common principles established by global regulatory frameworks with how these principles can be applied through local and regional measures. This is particularly challenging given that universal solutions are likely to be unobtainable as no two seas and/or coasts are the same in terms of biology, geology, physics or socio-economics. Therefore, solutions will have to be found on a sea and ocean basin scale and might differ from basin to basin.

Addressing regional and local versus global scales is likely to be complicated by the way research questions are framed and prioritized by different disciplines, and how local and regional stakeholders can influence management. There is a large divergence in priorities between natural and social scientists, highlighting great challenges for cross-disciplinary research cooperation, although cumulative stressors are important to both (Rudd, 2014).

A further task in reconciling global versus regional challenges is that global frameworks require national-level reporting, for example the voluntary national reviews of the SDGs. Nation states also have to comply both with their obligations at a regional level, such as EU legislation, and international obligations from e.g. treaties, and adjust their national legal and policy frameworks to meet requirements.

3.4. Conclusions and recommendations

There is an essential role for science in monitoring the impact, predicting, projecting and assessing change, prioritizing and identifying plausible actions, evaluating alternatives and informing society and policy. The management of multiple stressors while attempting to meet all European environmental regulations is extremely challenging. The role of science has been recognized by initiatives such as the UN Decade of Ocean Science for Sustainable Development and the ongoing desire to improve the science policy interface.

For research to address these multiple challenges, we need to move beyond concepts of multidisciplinary approaches to transdisciplinary science. We need to find innovative ways to address geographic scales and the interconnections of marine systems to each other and to the land. No one discipline or institution alone can adequately build the evidence base or tools required to answer these challenges. Such an approach can establish common management principles, while providing specific measures that can address the varied threats affecting marine ecosystems. For further information, see Chapter 6 on sustainability science.

Success will require a more coherent, strategic and integrated approach by the marine research community. Social and economic sciences will need to be involved in: 1) translating scientific findings on multiple ocean stressors into management actions that are supported and implemented by society, and 2) understanding the drivers behind human pressures. These will have to take into account all costs and benefits of human activities impacting the ocean and must include land-based activities such as fossil fuel consumption, agricultural practices, plastic production, atmospheric emissions and the use of rivers as conduits for wastewater. This collaboration between scientific disciplines is key to a sustainable future ocean, and the development and evaluation of informative future scenarios of global change.

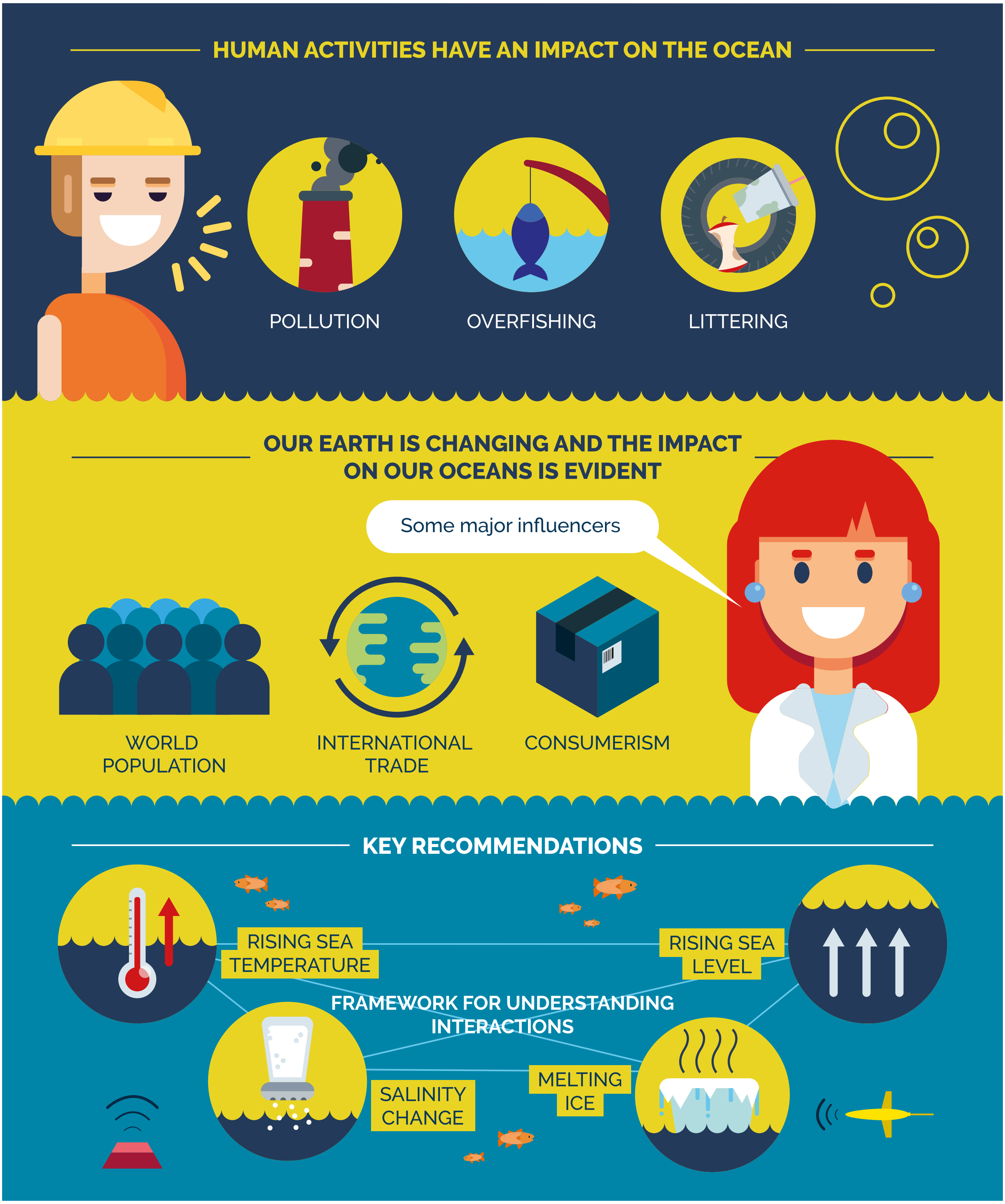
To address these challenges, we recommend the creation of a framework for evaluating the cumulative and interactive impacts of multiple stressors. This requires questions to be framed in a way that provides a continuum from the evidence, identifying and explaining marine and coastal processes, to the communication of information needed to inform policy and build understanding of the ways and means to transform existing practices so that performance measures and management strategies can be identified and implemented.

Although impacts from 2-3 stressors have been addressed in some European projects, the accumulation of all stressors has not yet been considered. To address this knowledge gap and ensure better management of marine ecosystems, novel research needed includes:

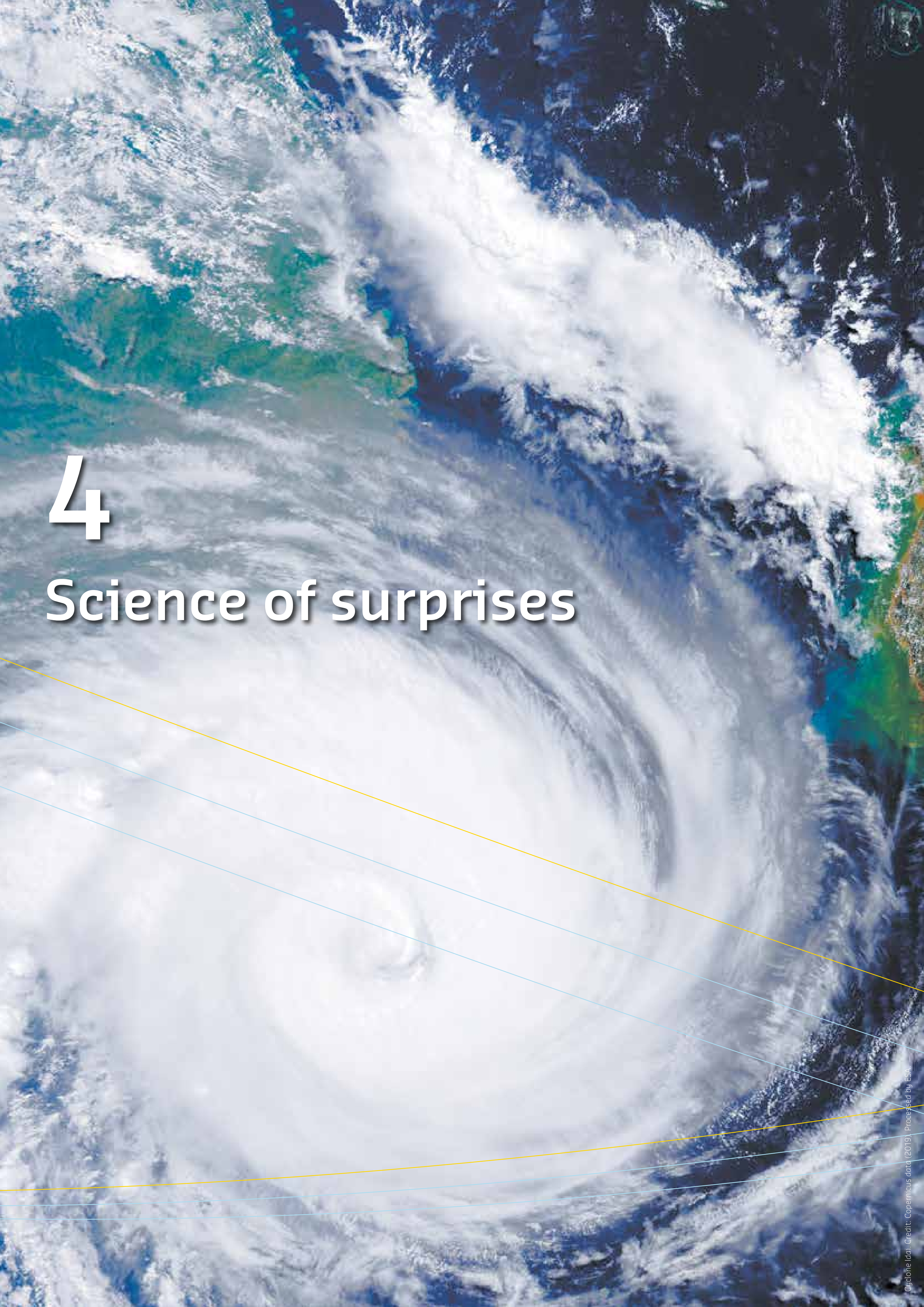
- The identification and evaluation of of cumulative effects of all stressors, or drivers, on the ocean from an ecosystem perspective;
- Exploring the impact of all stressors on the evolutionary responses of species to key drivers, such as climate change and the mechanisms and speed of adaptation over time;
- Studying the impact that all stressors have on the interaction between different species (e.g. between microbiota and multi-cellular organisms);
- Combining smart multi-stressor experiments with increased observations and scientifically sound models in a transdisciplinary approach. These experiments will be needed to underpin and validate quantitative multiple stress models and quantify uncertainties. They will help to develop early-warning indicators for multiple impact effects and approaching tipping points and help to prioritize management strategies of the marine environment; and
- Evaluating the effects of multiple stressors to provide an understanding of the mechanisms of consequent biological responses.
- Clear dialogue between all relevant stakeholders on management objectives to enable the successful implementation of management strategies and performance measures.

Credit: Sheila Heymans

The Eduard Bohlen ran aground in 1909 on the Skeleton Coast, Namibia. It now lies 400 m from the shoreline, an indication of the constant change in the coastline.


HUMAN ACTIVITIES HAVE AN IMPACT ON THE OCEAN
POLLUTION
OVERFISHING
LITTERING
OUR EARTH IS CHANGING AND THE IMPACT ON OUR OCEANS IS EVIDENT
Some major influencers
WORLD POPULATION
INTERNATIONAL TRADE
CONSUMERISM
KEY RECOMMENDATIONS
RISING SEA TEMPERATURE
RISING SEA LEVEL
FRAMEWORK FOR UNDERSTANDING INTERACTIONS
SALINITY CHANGE
MELTING ICE

4
Science of surprises



Cyclone Idai. Credit: Copernicus data (2019). Processed by ESA.

While long-term changes in climate are of great environmental concern, as described in Chapters 2 and 3, the greatest and most immediate local impacts on ecosystems and humankind will be caused by climate-related extreme events, geological hazards and accidents such as the Deepwater Horizon oil spill in the Gulf of Mexico and the Prestige tanker disaster of 2002 in Spain. On mainland Europe, extreme events include the floods of August 2002 that resulted in an economic loss of €9 billion in Germany alone and the heatwave in August 2003 that caused 15,000 excess deaths in France. Although extreme events also occur at sea, e.g. hurricanes or catastrophic mass mortalities of benthic organisms due to climate stress (Rivetti *et al.,* 2014), much less is known about their environmental and socio-economic impacts on marine ecosystems and ecosystem services. The earthquakes and tsunamis in Sumatra (2004) and Japan (2011) both caused substantial casualties and economic losses and had not only regional but also global impacts.

Extreme events can be identified as being rare (less than 10% probability), intense (i.e. events that have large deviations from mean environmental conditions), and/or severe (i.e. events that result in large environmental and socio-economic losses or human casualties) (Beniston *et al.,* 2007). An increase in rare and intense extreme events can result from an upward or downward shift in mean conditions (e.g. an increase of annual temperatures due to increasing occurrence of summer heat waves) and/or in an increase in the variability of these conditions (e.g. increasing rainfall variability within a year due to increase in droughts and downpours).

Although many systems respond gradually to climate change, some systems have tipping points where a small change or an anomalous pulse (as can occur during an extreme event) can trigger the system to change to an alternative stable state that is not easily reversible. For example, the abrupt changes in fisheries in the North Pacific ecosystems in 1977 and 1989 might have been due to fluctuations of North Pacific sea surface temperature becoming less frequent and longer lived, making the systems more prone to undergoing larger climate-triggered abrupt shifts (Boulton & Lenton, 2015). Models imply that such changes in climate fluctuations may promote self-sustained shifts to alternative stable states in climate-sensitive systems (van der Bolt *et al.,* 2018). Other phase shifts can occur for example due to overfishing, leading to jellyfish invasions followed by harmful algal blooms, as described by Boero & Bonsdorff (2007) for the Adriatic Sea.

Credit: Mert Gokalp

Intense overfishing may lead to jellyfish invasions.

Extreme events and their impacts can be considered at various temporal (from past to future) and spatial (from local to global) scales. The rarer the event, the more difficult it is to identify long-term changes in the frequency of its occurrence. For example, an exceptionally high precipitation event in California during the winters of 2015–2016 and 2016–2017 that caused severe coastal erosion (Barnard *et al.,* 2017) was rare (i.e. highly unusual) but not unprecedented when looking back at events almost 150 years (Reynolds *et al.,* 2018) and 9,000 years ago (Du *et al.,* 2018). Looking back at past extreme events might help to identify changes and frequency in future events.


Credit: Pixabay

Volcanic eruptions can have large-scale and long-term impacts on atmospheric processes followed by altered temperature, sea level and ocean circulation.

Local events can also have long-distance effects. For example volcanic eruptions can have large-scale long-term impacts on atmospheric processes followed by changes in the temperature, sea level and circulation of oceans (Stenchikov *et al.,* 2009), as was seen in the impact of the Krakatoa eruption in 1883. Submarine landslides associated with slope instability, potential failure of volcanoes and methane release from gas hydrates associated with pressure and temperature changes, can also have major impacts.

More recently, it was found that marine organisms can also be impacted by events over long distances. For example, climate-induced mismatches in food availability for migratory seabird chicks in the Arctic in one year was followed by shifted predation on local benthic communities at their overwintering grounds in Africa two years later (van Gils *et al.,* 2016).

Extreme events impact marine ecosystems and, subsequently, the services they provide. For example, the 2012 ocean heatwave was the most intense warming event in the North-West Atlantic in the last 30 years and triggered an earlier inshore movement of lobsters, making them more susceptible to fishing. The extended fishing season and high landings finally resulted in an economic crisis in lobster fisheries (Mills *et al.,* 2013). Consequences of marine heat waves will be particularly severe in parts of the world that rely heavily on marine fisheries for both nutrition and economic benefit such as West Africa, the Bay of Bengal and South-East Asia (Barange *et al.,* 2014). In addition to known ecosystem services, marine ecosystems may also provide as yet undefined benefits such as mitigating temperature variations for ecosystems that are vulnerable to extreme events. For more on valuing marine ecosystem services see the EMB Future Science Brief N° 5 (Austen *et al.,* 2019).

Insight into the mechanisms that underlie extreme events and the resilience of marine ecosystems may help in designing strategies to build a safe operating space for human activities within these systems. (Scheffer *et al.,* 2015). These strategies should not only take the potential impacts of extreme events into account, but also factors and developments such as climate change and multiple stressors as discussed in Chapters 2 and 3.

Credit: Pixabay

The 2012 heatwave in the North-West Atlantic triggered early inshore movement of lobsters causing high landings and eventually resulting in an economic crisis in lobster fisheries.

4.1. Trends and expectations

4.1.1. Storm surges

Coastal flooding poses a significant risk to life and infrastructure, with wide-ranging social, economic and environmental impacts. In coastal cities worldwide, flood exposure is increasing due to the changing climate, population growth and subsidence. Allowing for investment in adaptation measures, global flood losses in 136 of the world's largest coastal cities have been estimated to rise from US$ 6 billion per year in 2005 to US$ 60–63 billion per year in 2050 (Hallegatte *et al.,* 2013). Storm surges – the episodic effect of the weather on sea level – are often the most important components of extreme sea level and can episodically raise the sea level by 3 m when caused by extratropical weather systems and over 9 m when caused by tropical systems.

The multi-decadal variability of winter storms – and therefore storm surges – is dominated by natural variability. The occurrence interval of extreme storm surges is longer than our current records of atmospheric conditions (from weather stations) and sea level (from tide gauges) so they provide only a few examples of the most extreme storm surges. For example, in the North Sea there are only records for two noteworthy storm surges, which occurred in 1953 and 2013 (Wadey *et al.,* 2015). This begs the question – could an as yet unobserved weather system resulting from natural variability invalidate the extremely valuable statistics typically used for the deciding on coastal defences?

For tropical cyclones, it is possible to generate many thousands of modelled events (Lin & Emanuel, 2016) by embedding relatively simple cyclone models within large-scale climate models. We also need to devise computationally efficient methods of synthesizing a large ensemble of mid-latitude weather systems to force storm surge and wave models.

Credit: M. Mackey

Natural variability of winter storms may produce devastating storm surges, causing local sea level rise between 3-9 m.

Cyclones have consequences for marine ecosystems, in particular due to changes in wind-driven physical disturbances in the water and on the sea floor. Relatively long periods with low or no physical disturbance create "windows of opportunity" for marine organisms that require low disturbance conditions to establish new communities (e.g. mangrove seedlings can establish themselves on tidal flats). A subsequent large storm can then result in a sudden shift to new environmental conditions, for example a shift from salt marshes or mangroves to bare tidal flats (Balke *et al.,* 2014).

Credit: Sheila Heymans

Cyclones can impact mangrove forests causing shifts in ecosystems.

4.1.2. Heatwaves and harsh winters

Marine heatwaves are predicted to increase dramatically in frequency and magnitude as a consequence of global warming (Frölicher *et al.,* 2018), but their ecological effects, particularly in marine ecosystems, are poorly understood. Impacts have been documented during the 2003 heatwave in the Mediterranean Sea (Garrabou *et al.,* 2009) and the Western coastal waters of Australia in 2011 (Wernberg *et al.,* 2013). In Australia thermal stress resulted in mass mortality of benthic macro-invertebrates, reduction of habitat-forming kelp followed by knock-on effects on the associated benthic communities and the domination of fish communities by tropical species. Exposure to such high temperature anomalies can be directly lethal causing metabolic dysfunction, or indirectly lethal when increased respiration rates lead to energy shortage and trigger the development of pathogens (Garrabou *et al.,* 2009). In the Mediterranean Sea these mass mortality events have been linked to thermal anomalies for the past 50 years (Rivetti *et al.,* 2014).

In temperate seas, such as the Wadden Sea, harsh winters have historically resulted in high mortalities and locally extirpated worms, bivalves and fish in coastal and offshore waters. As with high temperatures, severe low temperatures can also be lethal either directly from a lowered functionality, or indirectly from a higher vulnerability to disease (e.g. Crisp, 1964). Such mass mortality events are generally followed by recolonization of other, invasive species, or juveniles of the same species (Beukema & Dekker, 2005). If the frequency of severe winters decreases and that of hot summers increases, shifts in mass mortalities and recolonization events (including recruitment) are expected to have a significant effect on temperature-sensitive organisms and change marine communities.

4.1.3. Dynamic sea-floor processes and natural hazards

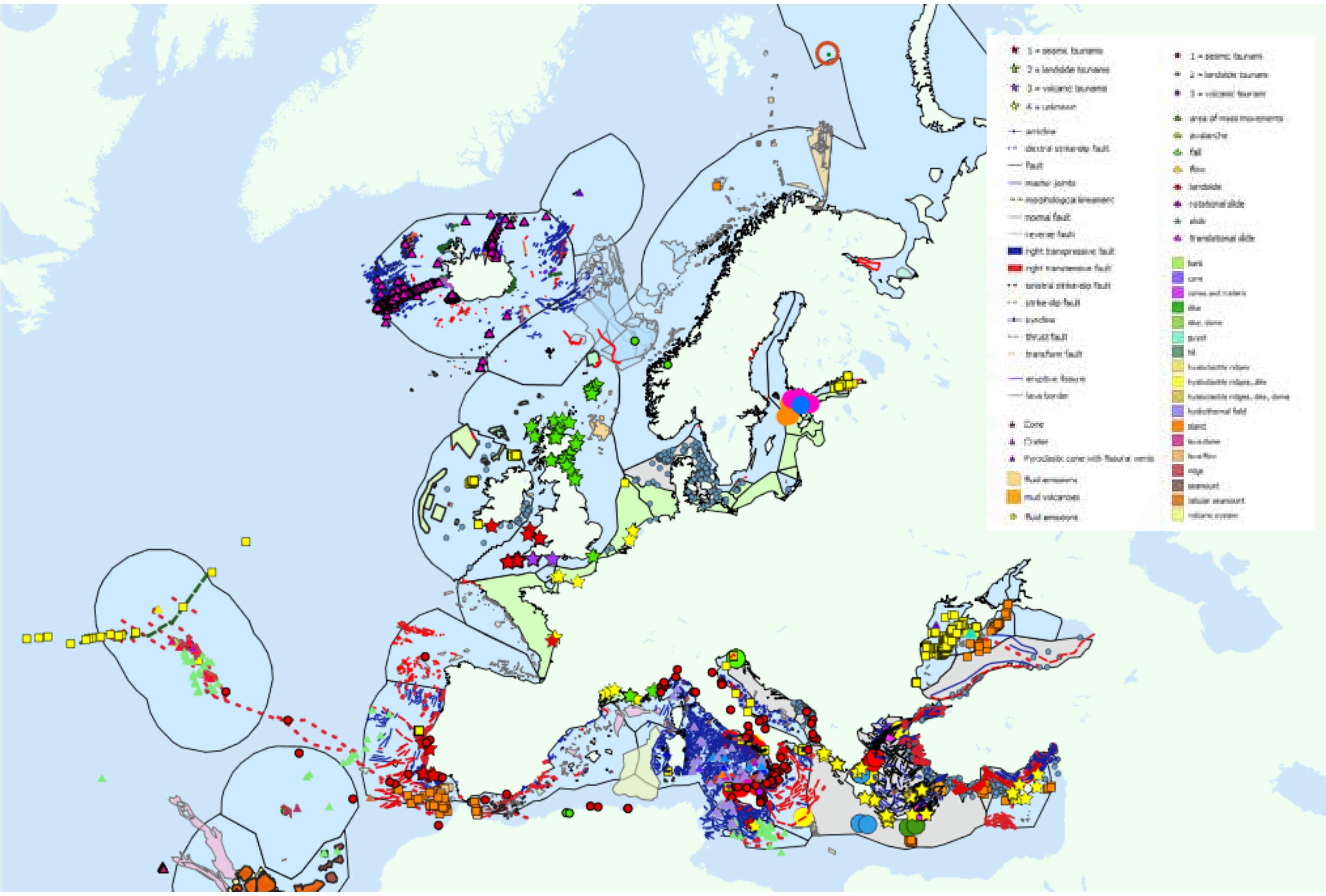
Marine geological hazards that originate in the ocean often have extreme consequences for our modern, globally connected societies. Natural hazards related to seafloor processes include earthquakes, massive landslides, volcanic eruptions and associated tsunamis, seabed liquefaction and methane hydrate breaches and occur on various scales in time, space and magnitude (Wallmann *et al.,* 2018).**With a growing proportion of humankind living close to the sea and depending on a number of oceanic services, our societies will become increasingly vulnerable to natural oceanic disasters** (Ten Hoeve & Jacobson, 2012).

In order to prepare for future events and to design and implement risk management strategies (Rosen, 2016), we need to understand the chain of triggers, progressions and shoreline-crossing impacts (including possible cascading effects) of geological hazards (Urlaub *et al.,* 2018).

The overall number of casualties from natural hazards has declined over the last three decades largely due to the efforts in making construction more resilient and with more adequate urban planning and early warning systems. However, singular events of high magnitude and impact do not necessarily follow this trend, as documented by the 2004 Sumatra earthquake and the 2011 Tohoku-Oki earthquake and associated tsunamis. These events represent fundamental geological processes on our planet, which cannot be controlled or channelled, and consequently an accurate hazard and risk assessment for individual processes and regions is of critical importance. Understanding the mechanisms that trigger potentially hazardous events is a prerequisite to fully understanding their hazard potential (Lay *et al.,* 2011).

In order to achieve a complete systems understanding, we need to integrate individual measurements that document the evolution of an event in space and time over long timescales to identify potential preconditions or precursors (Urlaub *et al.,* 2018). This approach becomes feasible now as the new generation of sea-floor sensors is capable of registering signals at high resolution over long periods of up to 10 years and can be used as multipurpose instruments for sea-floor monitoring and early-warning systems (Cruz Atienza *et al.,* 2018).

Following the 2004 Sumatra earthquake and the subsequent devastating Indian Ocean tsunami, there was widespread reappraisal of tsunami risk for Europe (DEFRA, 2005). For the Atlantic region, the most likely source of a seismic tsunami is the Azores–Gibraltar fault zone, which was responsible for the earthquake and tsunami that caused the destruction of Lisbon in 1755 (Baptista *et al.,* 1998). This fault is thought to have a recurrence interval of about 400 years, which implies that a future tsunami from this source is feasible. In the Eastern Mediterranean, particularly the Aegean Sea,



Events and probabilities of earthquakes, submarine landslides, volcanoes, tsunamis, fluid emissions and quarternary tectonics in Europe. Visualized in the EMODnet Geology map viewer on 03/05/2019. Made available by the EMODnet Geology project implemented by EMODnet Geology Phase III partners, and funded by the European Commission Directorate General for Maritime Affairs and Fisheries.

tsunamis occur due to the geotectonic activity on average every 90 years (Papadopoulos *et al.,* 2014). However, the non-linear and non-periodic dynamics of complex systems such as these make predictions highly difficult, as has been shown by the recent events worldwide mentioned above, which were not predicted and had dramatic consequences.

Submarine landslides are possible along the entire continental shelf break between North-West Europe and the Atlantic Ocean, but the underlying mechanisms and frequency of these events are still not well understood. The best studied is the tsunami generated by the Storegga Slide – a submarine mass failure that occurred approximately 8,200 years ago on the Norwegian continental shelf and slope. Mapping of tsunami deposits (Smith *et al.,* 2004) shows that this landslide generated a tsunami that reached the Northern UK coastline and may have reached other coastlines of the North Sea. The Storegga Slide tsunami is the only landslide-generated tsunami confirmed to have occurred on European coastlines, although other possible tsunami deposits on Shetland are dated at ca. 5,500 years ago and ca. 1,500 years ago (Bondevik *et al.,* 2005).

4.1.4. Meteotsunamis

Meteotsunamis are atmospherically generated shallow-water waves caused by a rapid change in Barometric pressure, which displaces water. These waves have periods between 2 minutes and 2 hours and can be fatal (Monserrat *et al.,* 2006) and they occur episodically but frequently in Europe. Recent examples include the event in 2006 in the Ciutadella Harbour in Menorca and in 2014 in Odessa, North-West Black Sea. They can give rise to significant economic losses; for example, in 1978 a meteotsunami produced US$ 7 million worth of damage in Vela Luka Bay, Croatia (Sepic *et al.,* 2016).

Climate change could alter the frequency of the required meteorological conditions for these under-researched hazards, so further research is needed into their generation mechanisms and climatology. If meteotsunamis were to become more frequent, for example due to increased convective activity in a warmer atmosphere, then better observations of them from high-frequency sea-level measurements will be fundamental to coastal warning systems in European seas.

4.2. World Climate Research Programme Grand Challenges requirements

Understanding and forecasting extreme events, together with episodic events, and their probability of occurrence is a challenge that must be addressed by scientists at European and international levels so that our societies can build sustainable development pathways in a changing world. This challenge requires interdisciplinarity and a thorough knowledge of the systems. The framework of the World Climate Research Programme Grand Challenge Weather and Climate Extremes is useful to outline the developments required for science at the European level (Sillmann *et al.,* 2017):

1) What is the observation strategy necessary to understand and forecast extreme events and abrupt changes?

The strategy for enhancement of the global Earth system observation network must take into account extremes and abrupt changes. Advanced observing system simulation experiments (OSSE), including statistical analysis of probability distributions, must be performed when defining spatial and temporal resolution requirements for observations, and when choosing key areas of the ocean and coasts to monitor. The future evolution of probability distributions under climate change scenarios is a major unknown that must be better quantified. New technology must be developed to observe more relevant variables, to assess the risks of abrupt changes on ecosystems, for example a “bio-Argo” network[58], observation of intermittent mixing events, and high-resolution satellite images. Cheaper real-time tsunami warning technologies based, for instance, on seabed pressure sensing, could provide improved early warning and would enhance existing tsunami warning systems. *In situ* monitoring of sea-floor faults and slopes based on acoustic global positioning system (GPS-A) or fibre-optic cable observations will transform our understanding of extreme geological events. Such monitoring needs to be further developed to serve the dual-purpose of early-warning and long-term monitoring. Interdisciplinary strengths must be gathered in physics, geology, geophysics, mathematics, statistics and data science to combine large heterogeneous data sets and extract relevant information about rare events.

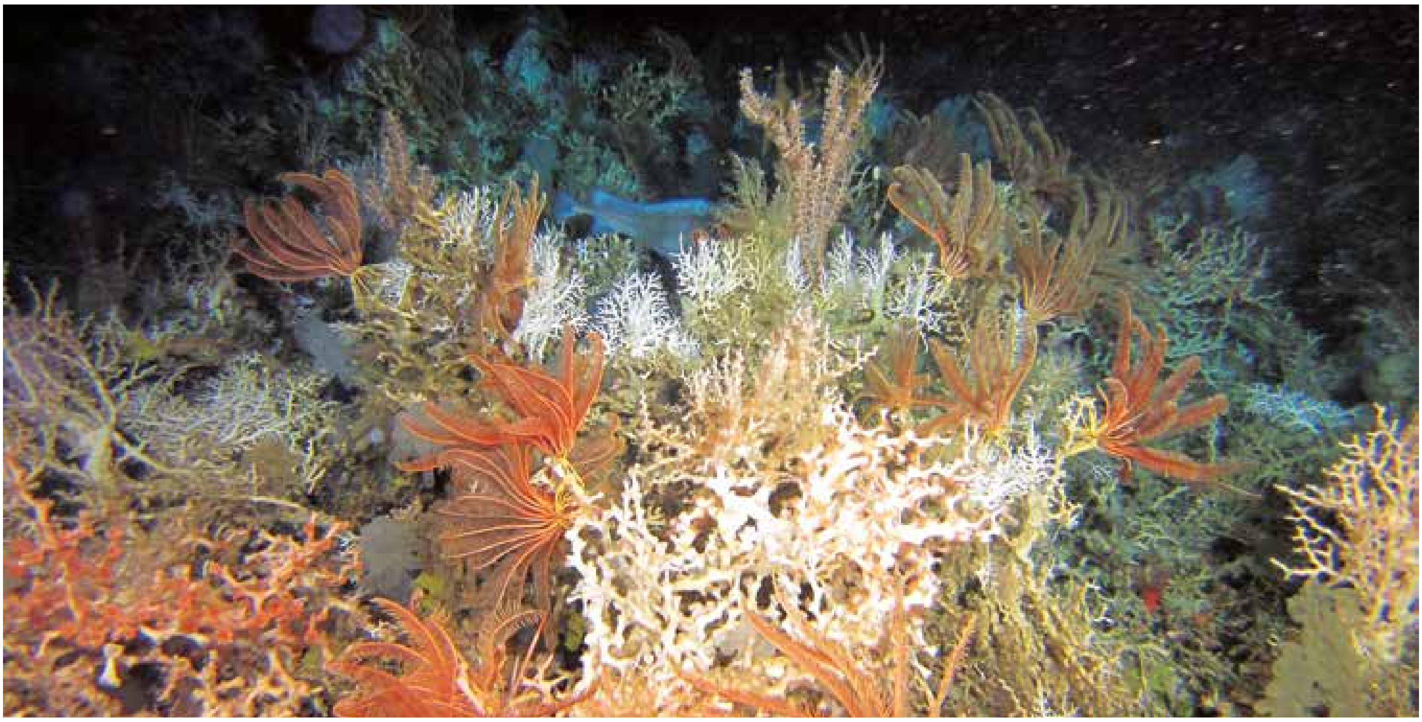
2) What are the drivers of extreme events and abrupt changes, and how do these drivers interact?

A deep insight into processes is the key to answering this question. International and interdisciplinary experiments should be targeted at the most dangerous extreme events and abrupt changes. These field experiments should be combined with mesocosm or laboratory experiments as well as numerical simulations. These experiments should include testing the thresholds in adaptability of marine organisms to cope with extreme events and abrupt changes. Targeted monitoring of geological systems needs to include multiple physical and chemical parameters to

Credit: GEOMAR

Deployment of a wave glider from RV SONNE offshore Northern Chile during a seafloor geodesy experiment for absolute positioning.

[58] http://biogeochemical-argo.org/



Extremes occur at the local scale (e.g. a single coral reef) but are often driven by large-scale conditions.

capture their transient nature. Our capacity to predict extremes is currently very low; therefore, the experimental strategy is in itself a research question: How do we find easily observable analogues that would be suitable to help us understand processes? How do we make better use of past observations, including paleontological records? Finally, "big data" will also be important in identifying the existence (or not) of tipping points in complex ecosystems where data are complex.

3) How can we evaluate and improve numerical simulations?

Extremes occur at the local scale (e.g. a single coral reef) but are often driven by large-scale conditions. High-resolution numerical models must operate seamlessly with large-scale or global-scale forecasts. This requires both theoretical advances and the enhancement of numerical tools. For forecasting rare events, ensemble strategies that combine different models are needed, but they are too often set aside because of their cost. More research into lower cost ensemble forecasting suitable for complex systems is called for. For rare events, we should also combine dynamic understanding with statistical approaches, such as Gaussian emulators and surrogate models, to better synthesize the low probability extremes that are most hazardous as they are least expected. Bridging scales from global to microscopic, using high-performance computing in combination with improved forecasting tools and monitoring, will provide crucial information on critical processes within the marine subsurface.

4) Can we attribute changes in the frequency or intensity of extreme events to specific natural and anthropogenic factors?

Unravelling the causal relationships and the different contributions leading to high impact extreme events is necessary in order to design mitigation strategies acceptable to humanity. Attribution techniques are an active field of research in the context of anthropogenic climate change; these techniques rely on the best modelling capabilities of climate centres and on widely distributed sets of numerical experiments (e.g. the Coupled Model Intercomparison Project[59]). Similar strategies should be developed in the context of the ocean and coasts submitted to multiple stressors e.g. anthropogenic warming and acidification, pollution, exploitation of resources, development of coastal infrastructures (see Chapter 3) and could build on existing international efforts moving in that direction: e.g. the Fisheries and Marine Ecosystem Model Intercomparison Project (Tittensor *et al.,* 2018). Identifying precursor signals to geological events will enable reliable forecasting of geohazards. Progress in the framing of uncertainties is also required.

In addition to these four challenges from the World Climate Research Programme, we suggest to address the following:

5) How do we couple physical, chemical and geological drivers with the response of ecosystems to extreme events in biological terms?

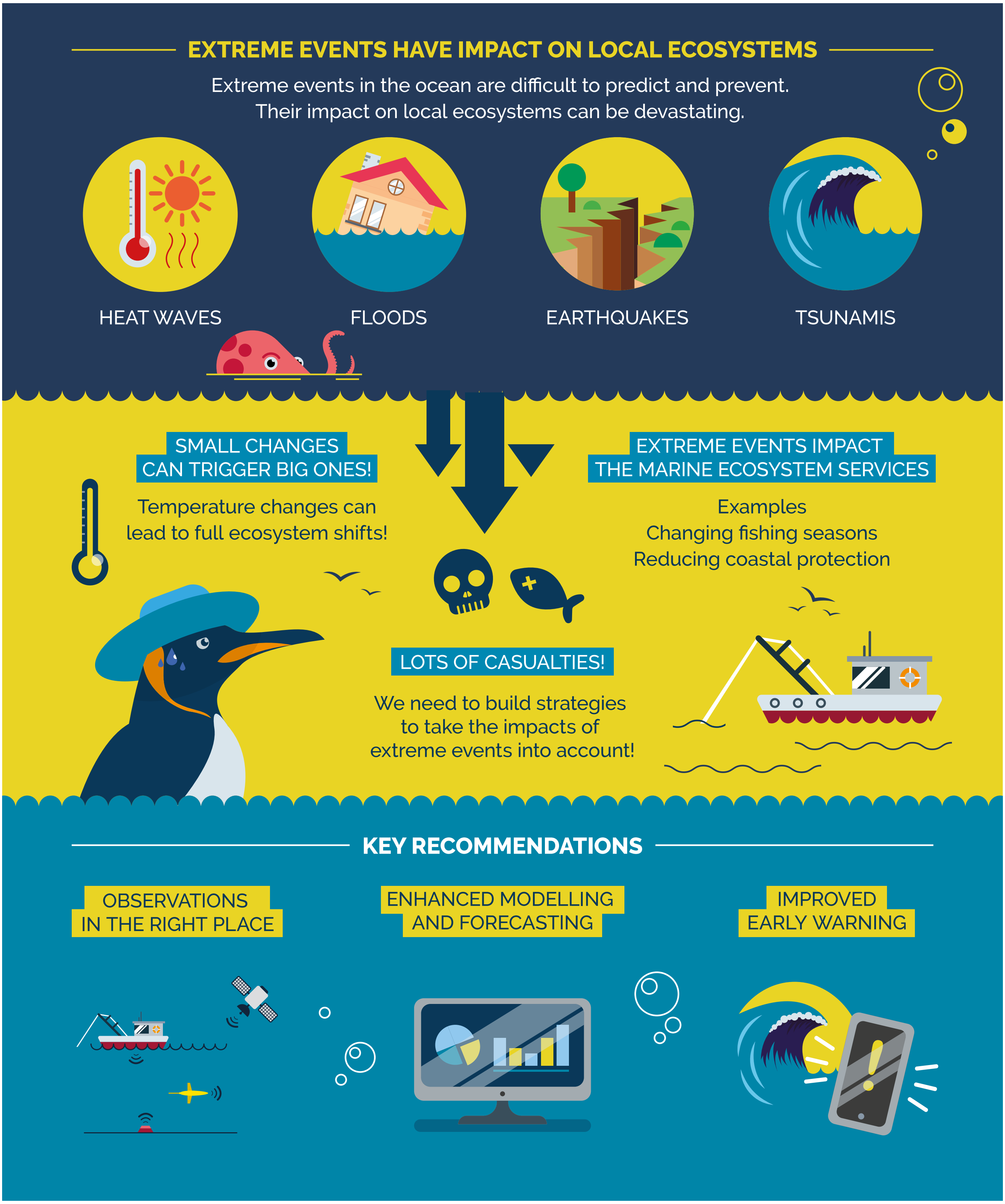
Besides the direct impacts on humans, extreme events also impact biodiversity and ecosystem functioning. The Marine Strategy Framework Directive (MSFD), with the definition of Good Environmental Status (GES), is focused on biotic responses rather than abiotic drivers and ocean observatories therefore need critical upgrades to include biological data (Benedetti-Cecchi *et al.,* 2018), which will give meaning to the measurement of stressors.

[59] https://cmip.llnl.gov/

4.3. Recommendations

Our recommendations for future research are:

- Development of enhanced observations that take into account extremes, which will enable a better early-warning system;
- Integrate regional predictions of glacial melt and wind and rainfall patterns from climate models with models of shelf-sea circulation to better understand the impact of weather on the ocean and particularly freshwater-driven stratification over all timescales;
- Research the chain of triggers, progressions, shoreline-crossing impacts and cascading effects of geological and ecological hazards to implement risk management strategies;
- Undertake accurate hazard assessments for individual processes and regions;
- Integrate measurements that document the evolution of an event in space and time over long timescales to identify potential preconditions or precursors for these events;
- Undertake further research into the generation mechanisms and climatology of meteotsunamis; and
- Gain a better understanding of the short-term and long-term impacts of extreme hydrodynamic, climatic and geological events on biota and ecosystem services.


EXTREME EVENTS HAVE IMPACT ON LOCAL ECOSYSTEMS
Extreme events in the ocean are difficult to predict and prevent.
Their impact on local ecosystems can be devastating.
HEAT WAVES
FLOODS
EARTHQUAKES
TSUNAMIS
SMALL CHANGES
CAN TRIGGER BIG ONES!
Temperature changes can
lead to full ecosystem shifts!
EXTREME EVENTS IMPACT
THE MARINE ECOSYSTEM SERVICES
Examples
Changing fishing seasons
Reducing coastal protection
LOTS OF CASUALTIES!
We need to build strategies
to take the impacts of
extreme events into account!
KEY RECOMMENDATIONS
OBSERVATIONS
IN THE RIGHT PLACE
ENHANCED MODELLING
AND FORECASTING
IMPROVED
EARLY WARNING

5

Novel technologies, data and modelling for ocean research

Credit: Shutterstock

Novel technologies and data handling methods are transforming our daily lives. We live in the Fourth Industrial Revolution defined by a holistic technological momentum that integrates the physical, digital and biological spheres. **We foresee a revolution in the way we observe, connect, share and utilize ocean data.**

This will require an open and seamless exchange of data. The key will be to build on existing data handling structures while strengthening the focus on real-time data exchange and building a common "ecosystem" of applications to exchange and utilize ocean data for societal and business usage. Machine–machine interfaces will be instrumental in achieving this.

While ocean science has lagged behind some disciplines, e.g. weather forecasting, there is the potential to improve this through a decisive ocean initiative. Ocean physics, biogeochemistry, biodiversity and our understanding of ecosystem function should benefit from more multi-sensor observing systems, integrating the spatial and temporal dimensions from space to the deep sea, and be combined with artificial intelligence to help manage and analyse huge flows of data. The surge in interest in the ocean, exemplified by the Food and Agriculture Organization's (FAO) desire to increase seafood production, international actions against plastic pollution, and the UN Decade of Ocean Science for Sustainable Development initiative, illustrates the potential for concerted action in developing ocean science. Novel technologies and data handling schemes, defining important challenges, attracting scientists and entrepreneurs, and developing innovative solutions to stimulate creative thinking will be key to success.

Knowledge-driven decision support is key to sustainable development of the ocean. As both nearshore and offshore human activities continue to expand, we will need to monitor a range of different biological, chemical and geophysical parameters and be able to process and interpret these to understand the cumulative impact of human activities on the structure and functioning of marine ecosystems, as is described in Chapter 3. Novel technology offers many potential solutions to these challenges but often there are long periods of stasis before new technologies pass a certain critical level, become commonplace and impact science and society at large. For example, machine learning has been around since the 1960s but has only now matured into a megatrend with revolutionary potential.

Novel technology has an important role in making new solutions available to address the societal challenges already described in this report as well as in transforming our monitoring of the ocean and seas and in enhancing marine science. For this reason, the UN 2030 Agenda, including the UN Sustainable Development Goals (SDGs) and the UN Decade of Ocean Science for Sustainable Development, has set the global agenda for future technological developments.

There is a great potential to increase the connectivity and availability of the information gathered at sea. This is particularly valuable for marine science since working at sea is logistically complex and incurs high costs leading to under-sampling, which hampers our understanding of the diversity, structure and functioning of marine ecosystems and our cumulative impact upon them. Therefore, novel data exchange and data handling tools play an important role in the sustainable use of our ocean and seas.

Credit: VLIZ

The research vessel RV Simon Stevin. Operating research vessels incurs high costs but they are valuable for marine research.

5.1. Observatories

Dedicated observations of the oceans were for centuries done by seafarers on expeditions with non-scientific purposes. These early ships of opportunity eventually took on dedicated scientific personnel, with Charles Darwin's expedition on the Beagle being the most well-known, and led to a revolution in the way in which we understand life on planet Earth. Dedicated scientific ocean expeditions started in the late 19th century with the Challenger expedition. Towards the end of the 19th century, several research vessels were purpose-built and the number of observations at sea increased rapidly. Similarly, marine institutes and stations for dedicated coastal observations became more prevalent in the 1880s. Along with this came new scientific instrumentation and nets for capturing the biota of the sea. The development of acoustic instrumentation during the first half of the 20th century revolutionized ocean observations and enabled us to start "seeing" the sea with sound. In the 1970s, satellites providing ocean measurements started to appear in a second revolution in ocean observation systems (Longhurst, 2007). The technological developments in moored, drifting and autonomous platforms have expanded the data collected from the ocean, although there are still glaring deficiencies in biological observations (Benedetti-Cecchi *et al.,* 2018). At the same time, modelling has developed and revolutionized our ability to forecast ocean ecosystems (Heymans *et al.,* 2018) and simulate atmospheric exchanges with the ocean. A key future milestone is the revolution in data connectivity, storage and analysis that is currently transforming the ocean science landscape. The Internet of Things (IOT) is an important ongoing technology trend that is likely to expand in more applications at sea, promising to revolutionize the acquisition and utilization of ocean data.

Below the surface, the ocean will remain strongly under-sampled and this will hamper our knowledge generation of offshore- and deep-sea ecosystems and their related issues. Facilitating the connectivity and usage of all ocean data will therefore be of great benefit to increase knowledge about various ecosystem components. There are many different types of observation platforms used to collect data and samples from the ocean. Remote sensing satellites were the first to disrupt the importance of traditional research vessels, enhancing our understanding of the ocean with regards to spatio-temporal dynamics in primary productivity, sediment transport, and mixing of water masses. The development of cheaper, smaller (nano- and micro-) satellites used for everything from vessel tracking and ocean colour to relaying data from cetacean probes (Guerra *et al.,* 2016), and the large increase in the number of ocean users, will revolutionize how we observe the ocean.

In recent years, the number and types of marine robotics – remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), unmanned surface vehicles (USVs), as well as gliders, benthic rovers and various hybrids – have increased substantially. However, these technologies are yet to have a groundbreaking impact on ocean sciences. Although there have been recent developments in control theory and communications for cooperative underwater vehicles and swarm intelligence (Lermusiaux *et al.,* 2016), this revolution is still ahead of us. Meanwhile, there have been major investments in various semi-automated ocean observatories e.g. SMARTBAY[60] and Balearic Islands Coastal Observing and Forecasting System (SOCIB)[61] that provide highly temporally resolved observations that are unique and enhance our understanding of ocean processes.

AUV ABYSS on cruise SO242/1 as part of the JPIOceans project "Ecological Aspects of Deep-Sea Mining".

[60] https://www.smartbay.ie/
[61] http://www.socib.eu/

Concept by Fernando Boero and artwork by Alberto Gennari (Boero *et al.*, 2016)

Observations systems currently cover mainly physics, chemistry and biogeochemistry. In order to face the requirements of Good Environmental Status (GES) evaluation, observation systems must be upgraded to also cover biodiversity and ecosystem functioning. Networks of marine protected areas and marine stations will have a prominent role in this upgrade.

Purpose-built UAV designed to sample whale blow. Pirotta et al., 2017.

The use of drones has substantially improved many land-based activities that previously depended on manned vehicles such as planes and helicopters. Drones make these activities much cheaper and they can also be used to study the surface of the ocean and organisms that dwell near the surface, such as kelp and marine mammals. Drones are now being developed to fly beyond the line of sight for visual observations and could be used in asset tracking and sensory data retrieval. Together with cheap micro-AUVs now being developed for recreational purposes, drones have great potential to increase crowd data collection and citizen science.

New discoveries in ocean science are often closely related to the use of new methodologies and technology. In terms of observation technology, some important current trends are miniaturization, reduced power usage, improved battery capacity, local processing of information, and increased connectivity between platforms and between platforms and users. These trends allow observations to be made from a greater range of systems and data to be processed so that they can be transferred in low bandwidth systems such as satellites, laser communications and/or by acoustic links in the sea. This allows an increase in data gathering from different parts of the ocean. Therefore, keywords for future developments are data fusion (integration of various data sources) through autonomous, near real-time processing of data, connected data collections, adaptive sampling (changing where and how often you sample based on on-board data processing), local processing and global communication of data. However, technological advances are still needed to measure biodiversity patterns and ecosystem function and processes. Currently, ocean observations are mostly funded at the national level although the majority of the ocean is outside national boundaries meaning that these areas are much less well monitored. Therefore, the most pressing problem is the lack of sustainability and an appropriate business model for ocean observatories that can enable long-term data provision for sustainable development. At a minimum, we need to have sustainable measurements of the Essential Ocean Variables (EOV)[62], which should include physics, biogeochemistry and biological and ecosystem variables.

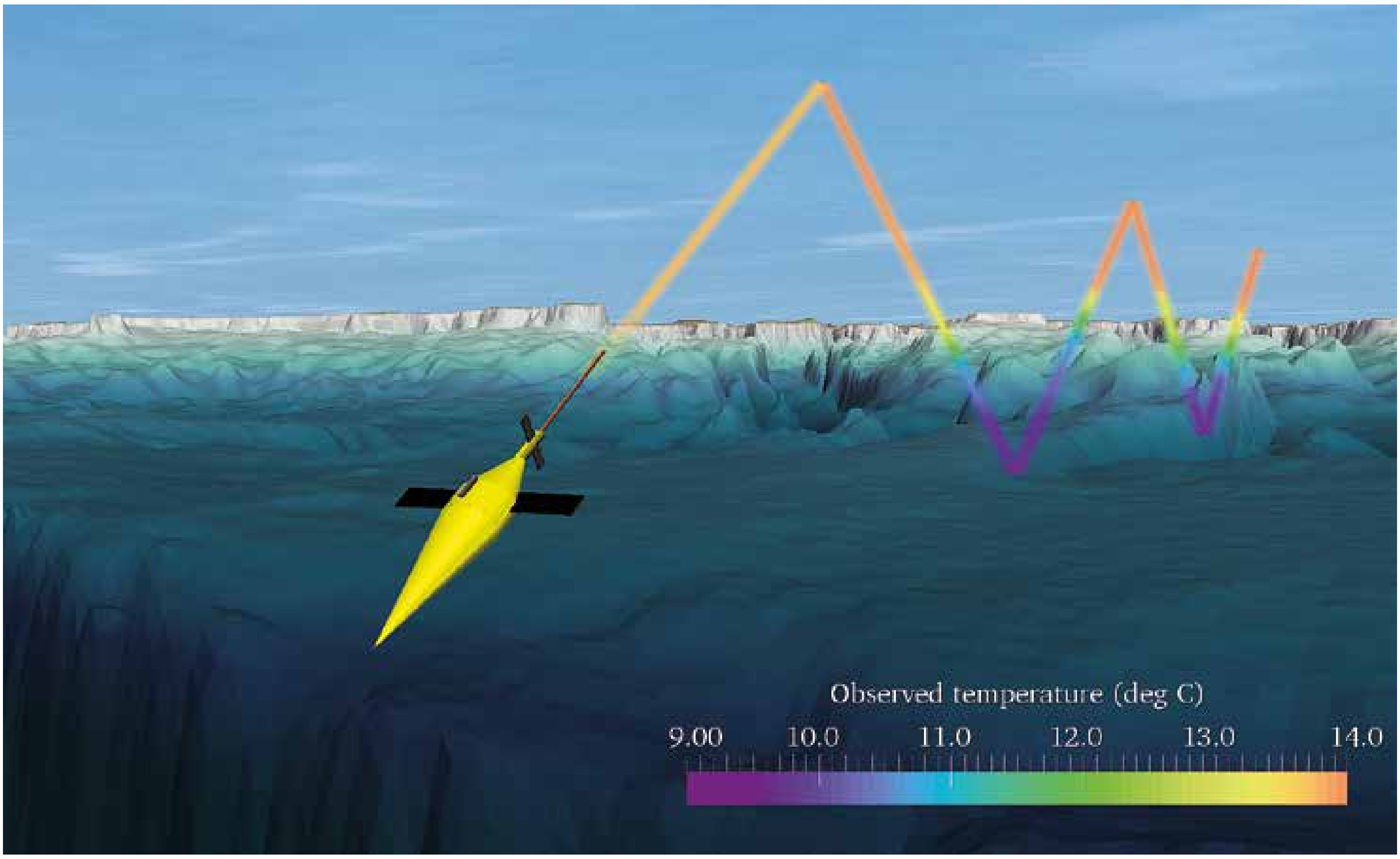
[62] http://www.goosocean.org/index.php?option=com_content&view=article&id=14&Item id=114

5.2. Instrumentation, systems, sensors and parameters

Observation platforms can utilize a vast range of different sensors for making physical, chemical, geological, geophysical and biological observations. Instruments are becoming smaller as tinier and less energy consuming parts are being developed. This also allows instruments to be fitted onto a wider range of platforms. The reduction in energy consumption in smaller instruments and improvements in battery technology increase the number of observations that can be made, allowing more highly resolved observations and longer time-series of measurements. Battery improvements coupled to reductions in energy consumption also enable autonomous marine robotics to sample high latitude areas where solar power is not an option. The increase in bandwidth seen in cities and homes has not taken place in the ocean, where communication is still restricted to costly and comparatively slow satellites. Local data processing is therefore needed to allow observations to be transferred to satellites or (submerged) acoustic communication networks in real time, which greatly expands the potential use of observations for operational purposes. In addition, *in situ* sensor data processing restricts the time needed at the surface for satellite communication of deep diving platforms such as gliders and AUVs, optimizing the current trade-off between time and energy spent making real-time observations, providing power to move the platforms and communicating with the shore.

Deoxyribonucelic acid (DNA) sequencing and profiling are some of the fastest developing technologies in the world. The increase in sequencing speed matched the gains in computing speed for many years but has now surpassed it by far. DNA barcoding is likely to become part of standard biological monitoring in the next decade, but molecular data must still be based on reliable identification of phenotypes, requiring taxonomic expertise. Portable DNA and ribonucleic acid (RNA) sequencers are already being deployed on research vessels as demonstrators, and autonomous sample processors are in full development even for the deep-sea. Together with methods such as hyperspectral imaging, broadband acoustics, underwater-LIDAR imaging and rapidly developing lab-on-a-chip applications for proteomics, transcriptomics and metabolomics, rapid *in situ* sequencing will play a major role in species identification, biodiscovery, biodiversity studies, population connectivity studies, etc.

Remote sensing of the Earth's surface through space-based and aircraft-mounted sensors has become a quintessential oceanographic tool for observing and mapping the horizontal distribution of physical, optical and biological near-surface processes, as well as estimating their vertical structure by



Credit: Sam Jones

Example of a glider mission between Scotland and Iceland.

developing area-specific algorithms. Earth observations at regional to global scales are critical for understanding environmental and climate change, especially with the development of new numerical approaches that can easily assimilate these observations into models providing nowcasts and forecasts for use in resource management and monitoring the status of the marine and coastal environment.

There are three key oceanographic parameters (ocean colour, sea surface temperature and sea surface height) that are routinely observed from space that play a major role in the Global Earth Observation System of Systems[63] (GEOSS) and the European regional programme, Copernicus[64], for monitoring the Earth system. Assimilation of these data into models requires knowledge of the uncertainty associated with each satellite product and the best possible accuracy in the data retrievals.

For remote sensing techniques to be a useful oceanographic tool for observing and quantitatively mapping near-surface features, there are several inherent limitations that must be reviewed. The signals received by the satellite sensors are weak because target reflectivity is not optimal; there are numerous contaminations from the intervening atmosphere, clouds and surface waves with multiple scattering distortions; and sensor contamination and drift can occur after launch.

5.3. Data

A major challenge in ocean science today is the "data debt" due to an accumulated lack of handling historical data collections in a way that allows seamless use, the transition of data into new storage formats, and making data readily available to all users. To avoid "data debt" in future hardware, it is imperative to establish a value chain all the way from the sensory instruments and platforms to the end user and all the steps in between, including safe and redundant storage. Ideally, the value chain should consist of machine-machine interfaces without the need for human intervention. The role of humans should be to oversee the process and handle errors, etc. The development of data products from the raw data is the key to making the most of the data collected. **The increased deployment of observatories with real-time data acquisition is a good example of the challenges and possibilities we are now facing.**

On the one hand, there is the storage problem – should all the raw data be stored? If not, what kind of resolution should there be? The next challenge is which data products should be developed? Should we monitor the data using machine learning and look for unusual patterns? And finally, should there be relations with other data sets to extract co-occurring patterns? Next generation marine observatories should be designed to provide adaptive sampling and open, secure, free and timely data access (Crise *et al.,* 2018). They should also be able to be integrated with long-term data series from marine stations. These data series keep track of historical changes and previous benchmarks, and they are hugely significant when modelling long-term changes in marine ecosystems.

There are many European and global initiatives for presenting marine data, including the European Marine Observation and Data Network (EMODnet)[65], SeaDataNet[66], Copernicus[67] and others. At their core are national data centres that are responsible forgathering data. It is important that data are readily available and are used and reused. Data publishing and curation should be findable, accessible, interoperable and reusable in line with the FAIR (Findable, Accessible, Interoperable and Reusable) principle (Wilkinson *et al.,* 2016). With the expected growth in the ocean economy, public-private partnerships on ocean data acquisition, storage and sharing will be a priority.

Modelled marine species' migration in response to changes in sea surface temperature between 1960 and 2009. Each point represents ocean species which are initially evenly distributed. As ocean temperature changes, each point is programmed to change its location in an attempt to maintain its 1960 'baseline' temperature (Molinos *et al.,* 2016). See animation for more details[68].

5.4. Numerical models

To provide realistic predictions about the state of the future ocean we need to develop and integrate predictive models from and with data (Heymans *et al.,* 2018). Ecosystem models have come a long way from the linearly interpolated, simple 3-functional group nutrient–phytoplankton–zooplankton models to today's complex, statistical (multifactorial probabilistic Gaussian mix or hybrid Markov models) and deterministic process-based models that extend from the plankton through the entire food web (with the potential to encompass entire socio-ecological systems). Data gaps are increasingly solved by new methods such as fuzzy logic methods or dynamic time warping. Models of ocean dynamics are based on well-known fluid dynamics equations. However, numerical models at the regional or global scale cannot explicitly resolve processes at the kilometre to metre scale that are key for global energetics as well as for coupling

[63] https://www.earthobservations.org/geoss.php
[64] http://marine.copernicus.eu/
[65] hhttp://www.emodnet.eu/
[66] https://www.seadatanet.org/
[67] http://marine.copernicus.eu/
[68] https://samcjones.com/data-visualisation/rate-of-climate-change/

with ecosystems. Physical models include these small scales in the form of empirical laws called parameterizations. Moreover, unlike weather models, ocean forecasts lack the high-resolution/high-frequency network of observations that is needed to parameterize, calibrate and validate these models. For instance, heavily used inshore areas have gaps in observations and understanding of the processes that govern change, which is compounded by the lack of adequate numerical simulations that include all relevant processes (fine-scale ocean dynamics, surface waves, tides, water–sedimentation interactions, ecosystems).

High-resolution ocean circulation models need to be developed further and informed by a network of observations in the same fashion as weather forecasts are run operationally around the globe. Such models have been developed at the global scale and for European seas in the framework of Copernicus, but there is a need to improve their operational forecasts. This should be developed further using observing-system simulation experiments to plan the deployment of observation systems and take full opportunity of the integration of ecosystem components (Handegard *et al.,* 2013) that cover the complexity of living systems (Benedetti-Cecchi *et al.,* 2018). The development of these models would benefit from some infrastructure support such as sharing standard code and high-performance computing clusters.

5.5. Future trends

New developments in information technology will be crucial in shaping our usage of the ocean and generation of knowledge about, and management of, ocean-related activities. We should expect all data to be openly available to everyone in real time. This means that it will be possible to use a variety of tools, including mobile communication, to tap into data flows sourced from science, industry and the general public. Cloud computing systems should then be developed to harmonize such data flows and deliver products to our future society. Universal data formats, quality controlled data and open standards should be the basis for a layer of applications that exploit raw data. Within science, it should be the norm to provide data openly and free of charge, while business models will need to be developed where non-science customers pay for specific data products from developers of applications who reimburse data collectors with a fair fee based on usage. In addition, the European Commission and European Research Council's Plan S[69] to make all scientific publications open access will enhance the availability of science for all.

Credit: Mert Gokalp

Although many people live by the ocean, we have a limited understanding of ocean habitats due to our mostly brief stays in the ocean realm.

[69] https://www.coalition-s.org/about/

5.6. Towards a digital ocean twin

Although many people live by the ocean, we have a limited understanding of ocean habitats due to our mostly brief stays in the ocean realm. Environmental issues are not at the core of most education programmes, and the ocean is not seen as part of culture in some countries. Ocean literacy must be at the core of basic education programmes.

In the future, virtual reality software for diving into the sea would allow humans to explore the ocean. Thus, we propose the development of a common augmented or virtual reality platform where all information about the sea can be uploaded and used to describe how our underwater world really works. For example, when a research vessel takes a trawl haul and calculates a catch composition, this information would be entered into the virtual reality software and used to update the description of what is sampled in that location. If the trawl were to find that there were schools consisting of herring, mackerel and blue whiting, the density of each of these species could be associated with their digital twins in the virtual ocean, which could then be seen when "diving" into the sea at this particular location using a virtual reality diving simulator. There will of course be a lot of blank spots in the oceans where data will not be available. These should be highlighted and will help to identify future research areas. It will therefore be necessary to have a background model predicting what kind of organisms and habitats are in different places. When new information is gathered, the model would be updated and its predictions improved. Such a system would rely heavily on computer gaming graphics, but species would be made to look as close to reality as possible. A nice visualization has been developed for the Baltic[70], where serious gaming has been combined with ecosystem models and policy drivers for the Maritime Spatial Planning Challenge simulation game[71]. In this manner, there could be a direct link between survey activity and global visualizations immediately after a sample has been taken. Google Street View Oceans[72] already has some of these components but lacks the virtual ecological interface that is key to making the experience of the ocean "real".

5.7. Recommendations

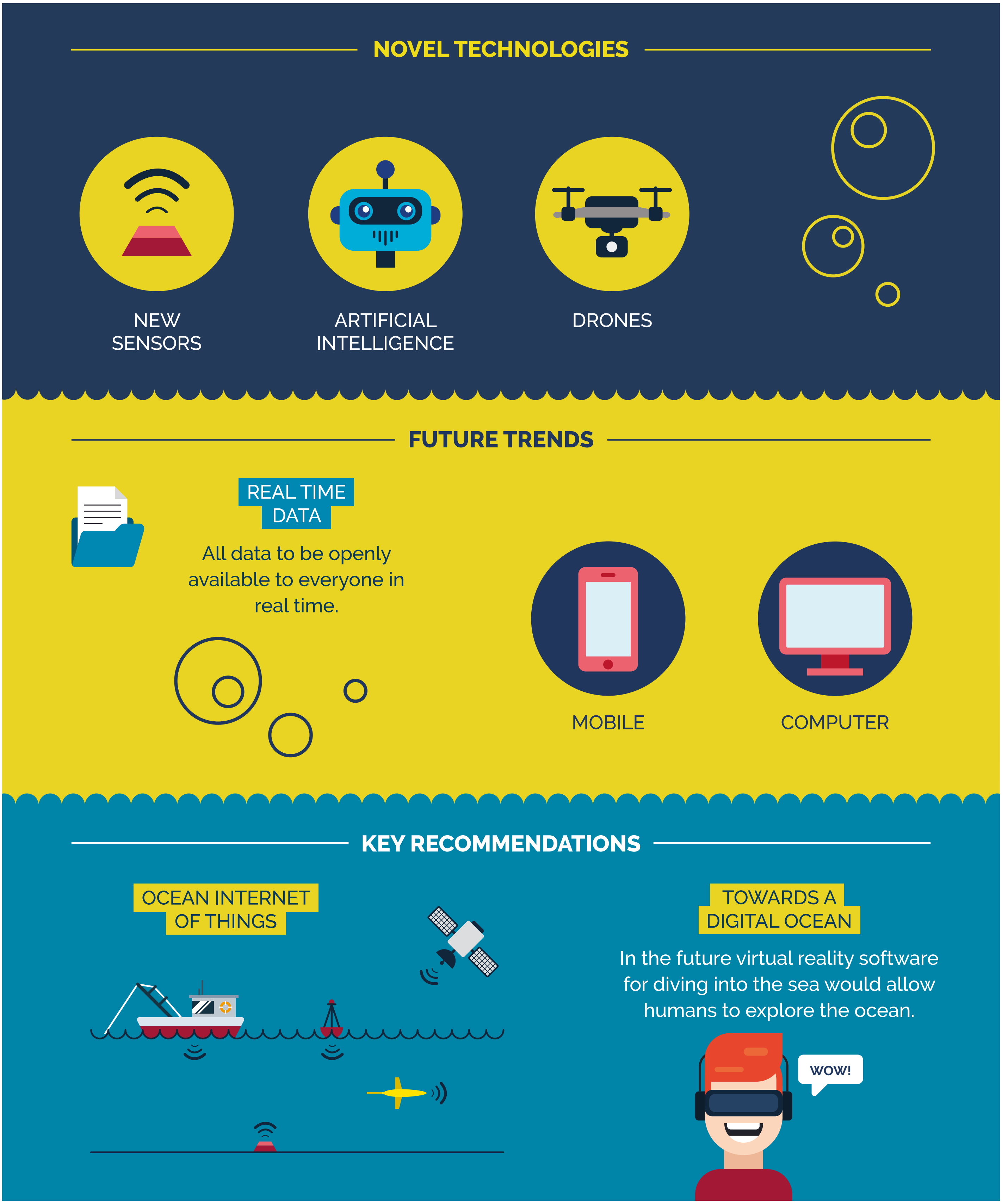
To enable future ocean research through new technologies, data and modelling we recommend:

- The development of a business model that can ensure the long-term sustainable funding of ocean observations;
- The development of an ensemble of numerical models for ocean forecasting that include an interdisciplinary framework to take into account physical, biogeochemical and biological processes as well as human activities;
- Designing the next generation of marine observatories to provide adaptive sampling and open, secure, free and timely data access;
- Assessing the quality of biological data and enhancing curricula to include basic knowledge of species diversity and biodiversity;
- The development of the Internet of Things (IOT) that includes ongoing technologies for use in the sea;
- Setting up local data processes that allow observations to be transferred in real time to satellites or other communication networks, e.g. submerged acoustics;
- Making all data readily available to everyone in real time; and
- The development of a common augmented or virtual reality platform where all information about the ocean and seas can be uploaded and used to describe how the underwater world works in real time.

[70] https://www.youtube.com/watch?v=XVkOAoiONdk&t=4s

[71] https://www.msp-platform.eu/practices/msp-challenge-simulation-game

[72] https://www.google.com/streetview/gallery/#oceans


NOVEL TECHNOLOGIES
NEW SENSORS
ARTIFICIAL INTELLIGENCE
DRONES
FUTURE TRENDS
REAL TIME DATA
All data to be openly available to everyone in real time.
MOBILE
COMPUTER
KEY RECOMMENDATIONS
OCEAN INTERNET OF THINGS
TOWARDS A DIGITAL OCEAN
In the future virtual reality software for diving into the sea would allow humans to explore the ocean.
WOW!

6 Sustainability science for the ocean

Credit: iStock


Credit: VLIZ

Tools for students to better understand how societal transformation happens need to be developed.

6.1. What is it and why do we need it in European marine research?

The need to transfer knowledge into action is an urgent imperative of the 21st century. Improving the management of our coastal and marine resources and the services they provide will help the world to transition to a more sustainable future. Coastal communities already face escalating risks, disasters and threats to livelihoods due to diminishing resources, climate change and sea-level rise. Addressing these challenges requires a different modality of science, which links different disciplines, knowledge systems and societal partners.

Traditionally, scientists have been trained to work and publish within their respective fields, with little connection between natural and social sciences. The world of marine science is no different (Ramesh *et al.*, 2015). As the world has become increasingly unpredictable due to increasing anthropogenic pressures forcing climate change, increased human population and consumption of marine resources, there is a need to move beyond single disciplines and towards an increase in transdisciplinary work among scientists.

At the international policy level, fulfilling the UN Sustainable Development Goals (SDGs) requires new levels of collaboration in order to address what are sometimes referred to as "wicked problems" associated with planetary change that have no known solution (Rittel & Webber, 1973). The high degree of connectivity in the marine space, and concentration of the human population in the coastal zone, sees many marine issues expressed as wicked problems.

Sustainability science (Box 6.1), which emerged as a concept in ca. 2000, provides a basis for dealing with the issues mentioned above (Kates *et al.*, 2001). This involves the need to reorient scientific practice to meet a sustainable development agenda for the ocean and seas (Cummins & John McKenna, 2010). Unlike other applications of research, sustainability science is not focused on expanding knowledge or improving innovation and competitiveness *per se*, but is centred on solving social challenges. The publication of the UN 2030 Agenda for Sustainable Development and the SDGs sharpened the focus on the need to develop the next generation of sustainability scientists (Stafford-Smith *et al.*, 2017), which is necessary to chart a course away from unsustainable, consumer-centric practices towards desired, sustainable futures.

BOX 6.1. WHAT IS SUSTAINABILITY SCIENCE?

Sustainability science is a transdisciplinary research agenda that points the way towards a sustainable society. It operates at the interface of natural science, social sciences and humanities, but is transdisciplinary – going beyond an integrated interdisciplinary approach by including different stakeholders such as knowledge producers and users. Alternative terms might include 'the science of sustainability', 'collaborative enquiry' and 'collaborative resource management'.

There is an opportunity to provide evidence-based support for policy makers to achieve sustainability of the marine domain within the context of major societal and planetary challenges. This includes taking stock of natural and human drivers on the marine food–water–energy nexus and the responsiveness of government, markets and civil society to the need for transformative action. For instance, Article 3 of the Marine Strategy Framework Directive (MSFD) refers to Good Environmental Status (GES) - "the environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive". However, other European policies do not necessarily take GES into consideration, such as planning objectives that consider growth without sustainability and disregard the cost of growth on natural capital.

Rather than allow capacity towards sustainability science to be built in an ad-hoc way, a strategic collective approach needs to be taken to building a community of sustainability scientists capable of advocating for innovative interventions for the benefit of Europe's ocean, seas and coastal zones. The vision is therefore to achieve a critical mass of capacity in sustainability science to ensure a step change in the way that European marine science impacts policy makers, practitioners and citizens to achieve the sustainable development of our coastal and marine resources.

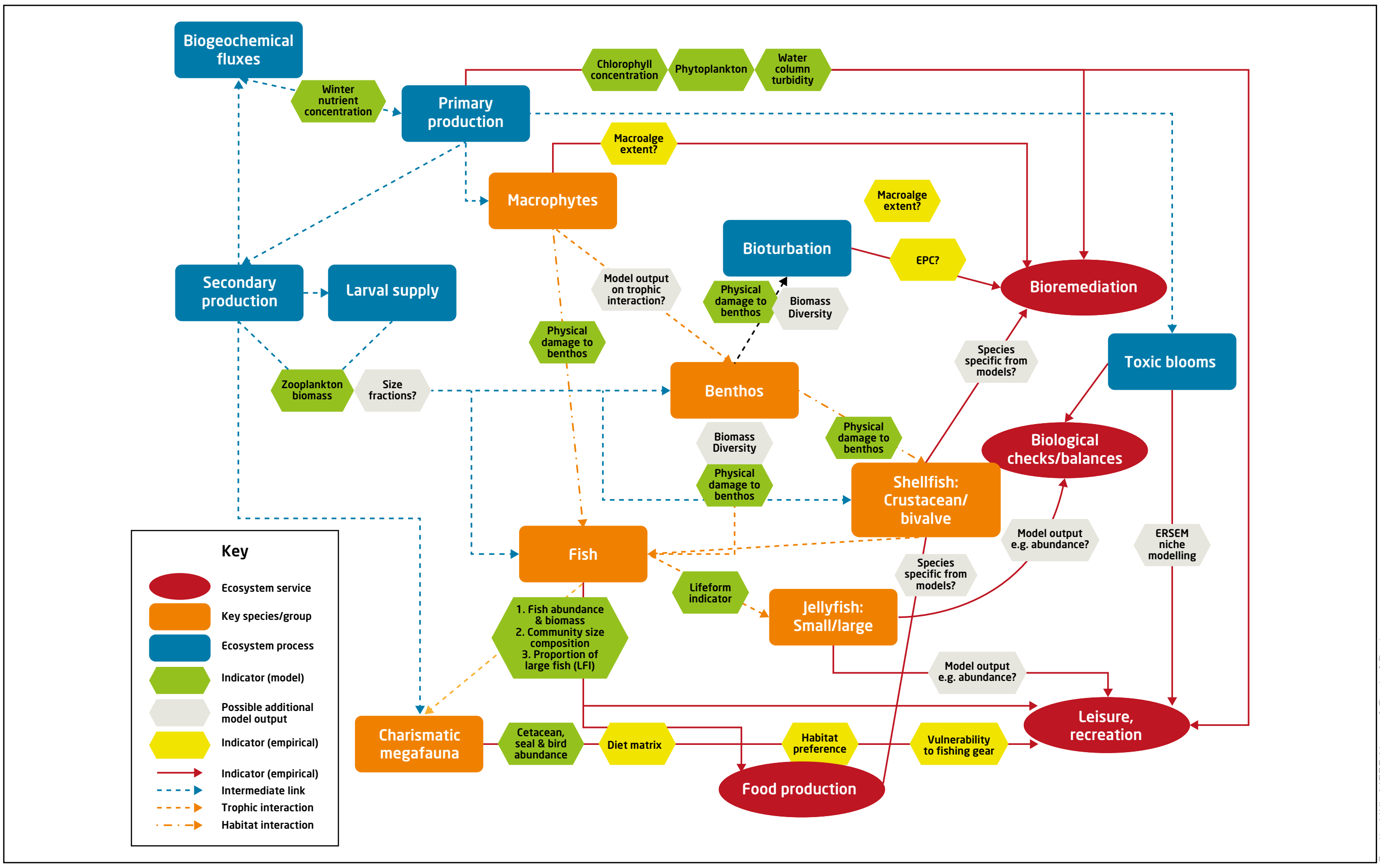
6.2. Key challenges

Key challenges facing Europe's marine environment arise from multiple and cumulative stressors associated with unsustainable practices (see Chapter 3). Blue Growth is adding new pressures in areas such as deep-sea mining, marine biotechnology, aquaculture and marine energy transitions. Current management responses, from the designation of marine protected areas, to the use of technology and disruptive innovation, are piecemeal and not fully effective in protecting people and the environment. Commercial fisheries are in decline; recreational fisheries are growing but their impacts are still largely unknown; eutrophication is a major problem in many coastal and estuarine areas; pollution from other sources such as plastics is a cause for concern; climate change is causing ocean warming, ocean acidification, storm surges, coastal erosion and sea-level rise. These issues are described in more detail in other chapters. The business-as-usual paradigm is no longer desirable and transformative change is required to transition towards more sustainable pathways. The interface between science, policy and society is one area that warrants increasing attention. Sustainability science influenced by a co-constructed design and social learning provides the roadmap for how this could be achieved.

The starting point for sustainability science as a whole is the recognition that many of these problems are formidable scientific and societal challenges underpinned by a sociotechnical regime that requires deep structural changes both at the economic, institutional and societal levels. The focus here is the challenge of delivering change in an interconnected world, featuring interactions between science, industry, technology, markets, culture, policy and civil society which impact the marine environment. This challenge highlights the role of multilevel governance, where decisions are made within and between these different interest groups, which struggles to reconcile conflicting and parallel demands for marine resource exploitation and protection.

Credit: Sheila Heymans

Impacts of recreational fisheries are still largely unknown.



Credit: UK's MERP Natural Capital Project

A network of the processes linking ecosystems and the services they provide.

6.3. Roadmap and recommendations

In order to achieve the sustainability science vision, a number of strategic actions need to be taken. Europe needs to develop a plan for marine sustainability science by promoting collective action at different scales that will:

1) Put the governance of sustainability at the core of a marine research agenda

The European marine science community should be mobilized to develop a solutions-oriented, integrated marine research agenda nested within a global effort to achieve impactful science. The objective is thus to build additional capacity to address the critical research gaps outlined below, while continuing with fundamental and applied research in areas to explore new horizons and to answer discrete questions. **Placing the governance of sustainability at the core of the marine research agenda puts a focus on the interface between understanding the dynamics of marine and coastal socioecological systems and how decisions are taken.**

The European Marine Board facilitates strategic discussions on the nature of research agendas and coordinates activities and research syntheses largely on natural sciences. However, putting sustainability at the core of research agendas will require broadening the scope of activities to include social sciences because the empirical basis for sustainability science needs to be deepened. A baseline review of current projects and research capabilities is needed because much can be learned from previous projects designed to explore systems-based approaches across multiple case studies. These include projects from the BONUS programme[73] such as BaltCoast[74], Horizon 2020 projects such as MUSES[75] or MAREFRAME[76], or Framework 6 projects such as SPICOSA[77].

[73] https://www.bonusportal.org/
[74] https://www.baltcoast.net/
[75] https://muses-project.eu/
[76] https://mareframe.github.io/dsf/
[77] http://www.spicosa.eu/

Integrative research needs bespoke funding to: build capacity to apply knowledge to the marine domain from scientists working in related fields of complexity; action research; and explore systems concepts in action and evaluation, transitions, futures, and organizational development.

The reality of the current approach to funding research is that it focuses on research projects of one to three years' duration. The co-design and co-production of knowledge with stakeholders, which is central to sustainability science, needs time to build mutual understanding and trust. This can be particularly challenging for marine environments, where stakeholders can be more dispersed than on land, and there is often a need to work across boundaries. Research design, and funding, should be more flexible to accommodate these issues, as well as the delivery of projects lasting more than three years. Funding should also cater for a diversity of methodologies. Traditional evaluation approaches are ill equipped to gauge the impact of innovative projects that deal with societal change. Programmes should adopt development evaluation measures (Quinn Patton, 2010) that can adapt to projects where outcomes emerge through engagement. This would be a step change in current approaches to marine research.

Tools to better understand how real and enduring societal transformation happens also need to be developed and leveraged as resources for students, researchers and managers. A good example of this is the two global knowledge repositories set up by the International Council for the Exploration of the Sea (ICES) Working Group on Resilience and Marine Ecosystem Services: One on social transformations of marine socioecological systems and the other on marine and coastal cultural ecosystem services[78].

2) Adopt core principles of sustainability science

The core principles of sustainability science (Figure 6.1) to be put into practice are to:

- Design policy-led and solutions-oriented agendas: The scope should be based on marine policy issues that place-based stakeholder groups identify and prioritize, in order to seek a mutually beneficial solution;

- Co-produce knowledge in collaboration with stakeholder groups: Policy makers and practitioners add value to the research process by contributing their local knowledge, professional experience and political realities. Their active engagement increases the opportunity for the uptake of research outcomes, gives greater legitimacy to co-designed solutions, and generates adaptive processes to find better and realistic solutions to sustainability problems;

- Implement an inter- and transdisciplinary approach: Adopting a systems approach requires a holistic framework to problem solving, implemented through inter- and transdisciplinary research. Together, natural scientists, geographers, sociologists, anthropologists, economists, historians, legal experts, political scientists, stakeholders and others can contribute to the understanding of nature–society interactions;

- Address Earth system complexity: Features of a complex system that arise from the relationships between nature and society include non-linearity, adaptation, transboundary issues and feedback loops. A systems approach is required to focus on complex and intractable problems and uncertain futures;

- Focus communication and research activities at the local level: The concept of 'think global, act local' relates strongly to the notion of local specificity. Local specificity relates to the significant role that local actors and contexts can play in delivering the global agenda of environmental sustainability through the implementation of cumulative local action. A key challenge to sustainability scientists is to work across these scales;

- Facilitate a process of social learning rather than providing definitive answers: Social learning is based on the mutual need for learning by doing, rather than the need to provide definitive answers. Social learning seeks to turn knowledge into action via a refined interplay between practice and planning;

- Practice science diplomacy: Science diplomacy reflects a common scientific effort to achieve cooperation among nations while building healthy and constructive transnational working groups to offer a sustainable successful approach to tackle grand socio-environmental challenges;

- Couple marine science with economics, law and policy studies: Marine science has always been deeply intertwined with societies' economic priorities, technological capacities and modes of governance. For marine science to support the sustainable development of the ocean, our empirical understanding of the ocean should be coupled with our understanding of the costs of economic activities and debates about legislative or policy options. The massive growth of aquaculture and the imminent exploitation of mesopelagic biomass (i.e. species living in the water column between 200-1000m) are examples of where a more integrative understanding of the ocean can support debate about what should constitute sustainable development. Similarly, in the face of deeply fragmented legal regimes governing high-seas fish, genetic resources and seabed minerals, marine science can offer more integrative insights into the impacts of deep-sea resource use. Thus, if scientific capacities are strengthened and science is engaged as a key stakeholder in debates about the conservation and sustainable use of marine resources, it can make a substantial contribution to implementing UN SDG 14.

[78] hhttp://ices.dk/news-and-events/news-archive/news/Pages/Social-systems-and-ecosystem-services-databases-launched.aspx

Credit: Gerald Schernewski

Research priorities need to be identified through a co-design process for a European marine sustainability science programme.

3) Address critical gaps in knowledge

Once the programme objectives and scope are established, some initial enabling mechanisms are in place, and core principles are included in the design of the capacity building process, research priorities need to be identified through a co-design process for a European marine sustainability science programme. The European marine science community should be supported to identify key questions that need to be brought to the scientific forefront and addressed together with societal actors.

Examples of the types of research questions to be addressed include:

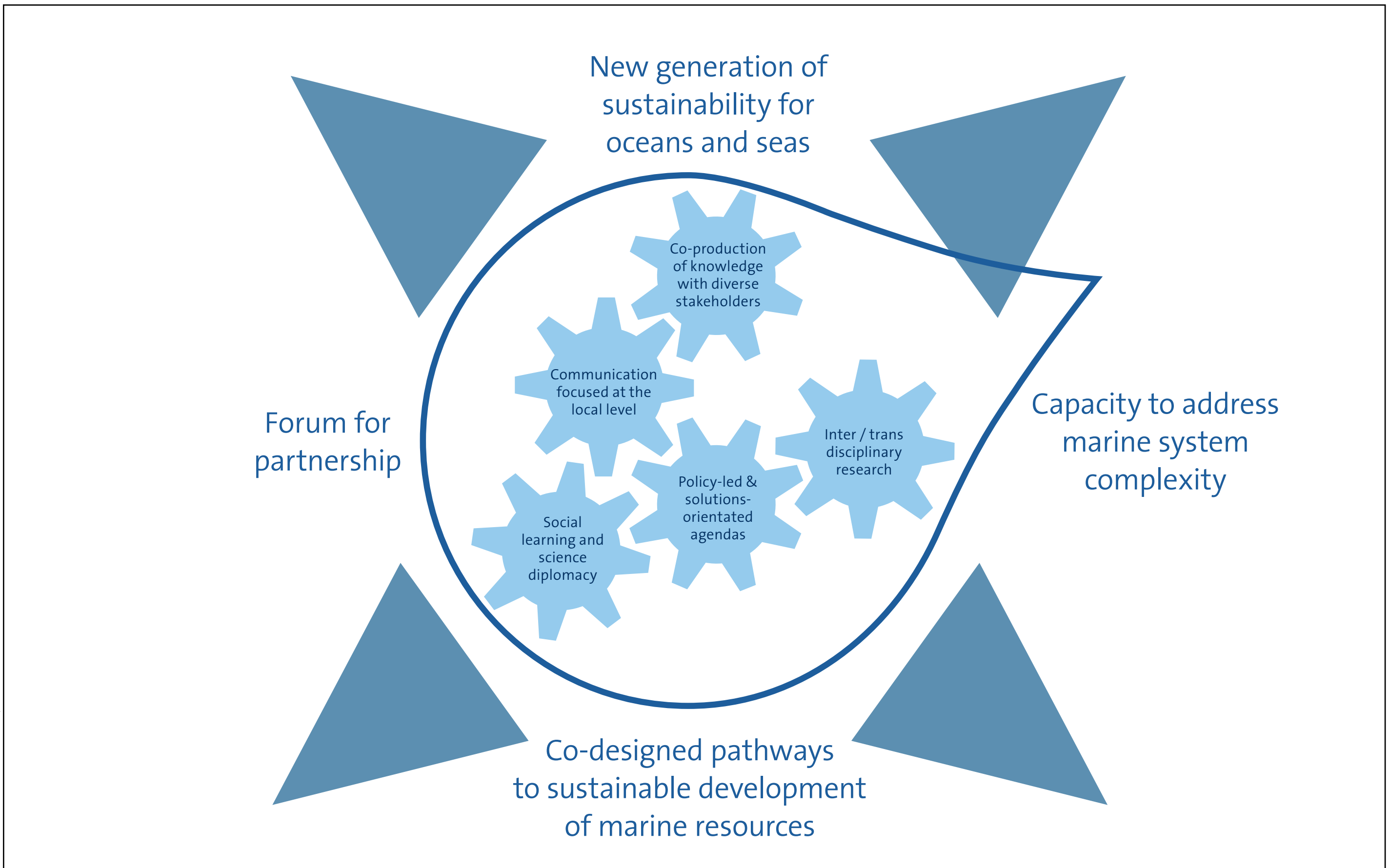
- How to achieve consistent European policies;
- How to strengthen the relationship between science and policy;
- How to build capacity for taking a systems approach and the unique transboundary challenges of managing marine environments;
- How to address the problem of the commons (shared ownership of marine resources), including the influence of private sector investment on marine and maritime affairs;
- How to deal with the imbalance in the distribution of wealth arising from unfair and unsustainable exploitation of marine resources;
- How to create political awareness of the threat of exceeding marine environmental carrying capacity;
- How to deal with a lack of joined-up thinking in approaches to decision-making, including the poor uptake of science policy recommendations; and
- How to analyse power dynamics and understand institutional behaviour in order to ensure an evidence-based approach to policymaking.

4) Develop a new generation of sustainability scientists for the ocean and seas

Addressing challenges of sustainable development requires a revolution in the training of future generations. This involves innovative pedagogical methods to help the next generation of scientists to think systematically and holistically about human–environment interactions. Lessons can be drawn from experiences in business schools, where case methods are used extensively to highlight "messy" contexts, or from the technology field, where the need to develop "data scientists" less than 10 years ago has led to this becoming one of the fastest growing employment areas.

Training and education need to be adapted at undergraduate and postgraduate levels. While many European universities have an excellent basis in marine science, programmes tend to be organized according to traditional lines, with a focus on areas such as marine biology, oceanography and engineering. Similarly, economics programmes lack reference to natural capital accounting and general assessment of ecosystem services. The human dimension of marine science has traditionally been lacking or poorly understood. While bespoke modules on topics such as ocean sustainability, ecosystem-based approaches to management, and innovation are abundant, integrated, holistic approaches to training for sustainability science and the associated social benefits are limited. Recent recommendations from the European Academies' Science Advisory Council (Thiede *et al.*, 2016) and the European Marine Board Future Science Brief N° 2 'Training the 21st Century Marine Professional' on this theme should be implemented (Vincx *et al.*, 2018) but should also include a sustainability science dimension. This should be implemented in parallel to enhanced training in traditional disciplinary areas to include skills such as engagement and science communication Programmes such as the European Commission's Erasmus[79] should be used to develop unique training prospects, particularly for postgraduate students. Other areas worth considering include a system of mentorship for early career scientists and opportunities for continuing professional development across educational institutions, government agencies, non-governmental organizations and corporations.

While the reward system associated with a research career is weighted towards academic publications, very little, if any, credence is directed towards benchmarks for alternative contributions to civil society, such as the formation of, or participation in, community groups or practitioner networks, which are fundamental components of the management process. This long-standing, macro-level issue needs to be considered at multiple institutional levels, with an opportunity for leadership at the European level, and in the marine domain. Lessons can be learnt from other regions or institutions (e.g. Commonwealth Scientific and Industrial Research Organisation (CSIRO)[80] in Australia that are now taking an impact oriented approach to judging the success of applied scientific efforts in the marine realm.



Credit: Francesca Malfatti, Valerie Cummins

Figure 6.1. Impact of the application of key principles of sustainability science to the European marine science research and capacity building agenda

[79] https://ec.europa.eu/programmes/erasmus-plus/node_en

[80] https://www.csiro.au/

5) Science and society

Citizen science, coupled with sustainability science, has the potential to drive changes in attitudes and behaviours, creating new windows of opportunity for successful transformations (Garcia Soto *et al.,* 2017; Villasante *et al.,* 2017). Citizen science, which commenced in the 1990s, refers to the collaboration between citizens and scientists in order to collect, investigate, analyse and report data from the environment under the auspices of a scientific project. Examples of marine citizen science projects do exist (e.g. monitoring jellyfish (Boero *et al.,* 2016)), and are growing. However, citizen science projects are currently still far more abundant in other fields, such as climate science, terrestrial biodiversity and environmental management, and this should be addressed.

This is not a panacea, rather an essential building block, in an equation that deals with public perception and stakeholder engagement as one of the most powerful forces for change, as advocated by those who argue for structural and fundamental changes in values and lifestyle. One such issue with perception is the distance between the citizen and the scientist, which is recognized as critical in preventing the development of a tight and sustainable coupling between society and science, (Shirk *et al.,* 2012). Although it is slowly changing, popular media in Europe often portrays images of scientists as middle-aged men handling vials in white laboratory coats, in contrast to the image of the "regular" citizen, often depicted wearing jeans and holding smartphones. These two contrasting pictures highlight the issue of conscious and unconscious bias, including the age, gender and professional biases that need to be overcome in order to form relationships between science and society.

Ocean literacy[81] refers to the broad concept of understanding the ocean's influence on our society, on us and on how we within our society are influencing the ocean. Ocean literacy, which proposes a research-based educational framework, was developed jointly among educators and scientists in the USA in ca. 2000 and has been promoted in Europe since 2015. It was designed to be easily used by educators in the classroom thus targeting future citizens. This is another tool to promote knowledge and help to bridge the gap between marine scientists and society, as acknowledged by the IOC-UNESCO (Santoro *et al.,* 2017).

6) Establish a sustainability science forum, including industry and civil society partners

There is a need for a forum within Europe that brings together all actors concerned with the complexity of sustaining Europe's marine resources that reaches beyond a narrow set of disciplines, fields or policy issues. Such a vibrant space would facilitate opportunities for cooperation between scientists, including social scientists, practitioners, officials, industry leaders and interested communities. A joint venture with other key organizations responsible for marine stewardship, including Future Earth[82], would help to deliver a forum that is credible, legitimate and salient.

Credit: European Marine Board

Marine citizen science projects are not abundant compared to those in terrestrial biodiversity.

Social sciences have an important role to play in influencing a range of human-related topics, such as social phenomena (e.g. markets, governance, politics and power), social processes (e.g. education, communication and development) and individual attributes (e.g. knowledge, behaviour, ethics, etc.) (Bennett *et al.,* 2017). The sustainability science forum should employ relevant tools from social science to deliver effective communication and engagement among diverse players.

It is critical that this forum includes industry leaders, who are often under-represented in the sustainability arena. Corporate social responsibility, stakeholder relations management and opportunities for innovating in the marketplace should be leveraged as drivers for industry engagement in the sustainability effort (Steurer *et al.,* 2005). Europe has the potential to influence and lead the global approach to capacity building in the management of the marine environment. Such a forum should also offer a focal point for international affairs by positioning Europe as a leader in the application of sustainability science for the ocean and seas.

81 hhttp://oceanliteracy.wp2.coexploration.org/

82 http://www.futureearth.org/

6.4. Recommendations

In summary, we recommend to:

- Put the governance of sustainability at the core of a solutions-oriented marine research agenda;
- Adopt core principles of sustainability science to the European marine science research and capacity building agenda;
- Address critical gaps in knowledge and develop research priorities for a European marine sustainability science programme through co-design;
- Develop a new generation of sustainability scientists for the ocean and seas;
- Increase marine citizen science to drive changes in attitudes and behaviours; and
- Establish a sustainability science forum within Europe bringing together all actors concerned with sustaining marine resources, including industry and civil society partners.


WORKING IN SILOS
SOCIAL SCIENCES
NATURAL SCIENCES
HUMANITIES
WHAT IS SUSTAINABILITY SCIENCE?
CENTERED ON SOLVING SOCIAL CHALLENGES
IMPROVING MANAGEMENT OF MARINE RESOURCES
KEY RECOMMENDATIONS
SUSTAINABILITY AT THE CORE OF MARINE RESEARCH AGENDA
NEW GENERATION OF SUSTAINABILITY SCIENTISTS
ESTABLISH MARINE SUSTAINABILITY FORUM

7

New frontiers, gaps and recommendations

Credit: Pixabay

A growing human population coupled with anthropogenic climate change, increased coastal development, consumerism and international trade are causing major changes to the ocean on a very large scale. Consequently, a significant priority should be the management of the ocean as a "common good of humanity" to secure a safe planet. The sustainable use of the ocean within planetary limits is required to sustain life on Earth and human well-being. Changes to the ocean are associated with the public good and well-being and the associated risks of potential impacts for individuals and collectives must be properly assessed and communicated, together with possible solutions for developing a sustainable future for the ocean.

The major changes impacting the ocean show four common characteristics which must be considered when thinking about the future ocean: 1) changes are very different at local, regional and global scales; 2) while some changes are already understood (e.g. increased sea surface temperature), others remain less studied (e.g. an increase in nanoplastics and other pollutants, seafloor processes, biodiversity erosion, changes in ecosystem functioning); 3) changes are often unpredictable in magnitude and effects (e.g. sea-level rise, ocean current regimes) and characterized by excessive perturbations of the environment compared to its natural carrying capacity (e.g. impacts from fertilizers, pesticides, CO_2); and 4) most of these ecosystem changes are probably irreversible (Scheffer *et al.,* 2015).

The integral role of the ocean in the Earth system and the immense scale of the problems require full integration of disciplines over the long term and at the spatial scale of the globe. For example, to explore the full complexity of interactions and feedback mechanisms of sea-level rise we must mobilize several disciplines in natural, health, and socio-economic science. The capacity for inter- and transdisciplinarity at various spatial and temporal scales is a major challenge for research. In addition, innovative approaches are urgently needed to strengthen the research–policy–society interfaces with an open and regular dialogue between decision makers. Therefore, scientists must anticipate problems before their consequences become extreme and answer cascading questions before the consequences of inaction become inevitable.

There are three main fields of marine research that are projected to be important in the mid-term horizon: 1) the ocean and climate change; 2) sustainable living resources; and 3) human activities and the ocean. As described in Chapters 2, 3 and 4, global warming affects the ocean in several ways: by impairing the cold part of the conveyor belt, making extreme events such as storm surges or marine heat waves more severe, causing distress to the biosphere, impacting coasts and sustainable living resources including fisheries and aquaculture, affecting the biological pump, and increasing hypoxia.

Credit: NOAA

International trade and shipping are set to increase by 2030.


Credit: Mert Gokalp

We need to improve our capacity to know how the ocean may change under future scenarios.

The growing demand for ocean resources and space intensifies and diversifies the direct and indirect interactions between humans and marine ecosystems. As shown in Chapter 3, the cumulative impacts of climate change, ocean acidification and eutrophication, non-sustainable resource extraction, land-based pollution and habitat degradation are threatening the productivity and health of the ocean as well as the sustainability of associated ecosystem services. In addition, the uncertainties of storm surges, tsunamis and dynamic sea-floor processes, as described in Chapter 4, make planning for a blue economy challenging.

As shown in Chapter 5, novel marine science technologies and modelling will help us to navigate the future, but we need to work as a one-planet global community. Charting scientific knowledge on a multidisciplinary virtual map has the potential to provide an outline of unknown, but conceivable, topics and research areas. We have not yet discovered most of the species in the ocean or how they interact to make ecosystems function. We have not mapped the submarine landscape at high resolution nor the communities that populate the sea floor, as we have done for the geology and biota on land. We understand from the planetary boundary concept and from the decarbonization goal of the UN Sustainable Development Goal 13[83] (SDG 13, Climate Action) that we need to function within the safe operating space of our planet in order for humanity to live and prosper and to achieve this we must understand how our planet functions.

7.1. Governance for a healthy ocean

Despite these growing challenges, there are opportunities to safeguard ocean-based human prosperity by regulating human–ocean interactions. Current governance of ocean use is not optimum due to fragmentation. Ecosystem-based management and the planning of maritime space are examples of good long-term policies and should be enhanced by the addition of a sustainability science forum as suggested in Chapter 6. However, there are still many unanswered questions regarding ocean governance such as: What new uses of the ocean are expected? What is fair and equitable benefit sharing between coastal states, the land-locked communities and the next generations? How can we address conflicts and trade-offs? How can more coherent, inclusive and effective ocean governance arrangements be reached? What are the prospects for binding international policies and what can cooperation at the regional scale offer?

In the face of uncertainty and changing economic and environmental drivers, there is a need to strengthen the links between science, society and policy because we cannot properly manage what we do not know. An important priority in developing a sustainable future for the ocean is improving awareness about human responsibility in climate change and finding the right level to act e.g. the UN, governments, multinational companies, fossil fuel companies and society at large. This is required to meet the emission targets set by the 2015 Paris Agreement and to limit warming to 1.5°C to 2°C relative to pre-industrial levels.

Governing the ocean space should benefit from international transdisciplinary cooperation with the following themes playing a key role in the sustainability of a "healthy ocean":

- Improvement in our capacity to assess the state of the ocean and how it may change under future scenarios;
- Enabling permanent dialogue between ecology and economy to fully exploit the potential for sustainable development associated with ecosystem services (provisioning, supporting, regulating or cultural) taking into account the interactions and conflicts between them;
- Development of integrated research programmes addressing the drivers and dynamics of the ocean's state and the cumulative impacts of ocean warming, acidification, extreme events, ocean pollution, land–ocean–atmosphere processes, as well as possible approaches to reducing impacts;
- Further exploration of human well-being trade-offs as in many cases, the desirable outcome of more energy, food, material or water produces unwanted chemicals, substances or simply wasted material. The amount of pollution is especially high in densely populated coastal regions, settlements and megacities. However, ocean circulation connects all regions of the globe and turns pollution into an ultimately global problem; and

[83] https://sustainabledevelopment.un.org/sdg13

- Fully integrating scientific assessment of resilience strategies, associated trade-offs and underlying ethical concepts for the ocean incorporated in decision support frameworks involving stakeholders.

Ocean sustainability and ocean governance can be addressed at different spatial scales, from the open ocean to the land–ocean interface at a particular beach. There are differences between geographical focal points in their level of governance, involved actors, the choice of governance instruments and their effectiveness. However, the need to use scientific knowledge to sustain governance mechanisms is always required. Developing and implementing sustainable governance strategies that safeguard ecosystem services and long-term ocean prosperity requires close cooperation between natural scientists, engineers, legal experts, social scientists, economists, policy makers and other societal stakeholders.

As far as legal and political governance instruments are concerned, the fragmented world order poses a challenge. There is no international authority with a global reach and a strong mandate that governs ocean affairs. Some global processes, like the UN World Ocean Conference series[84], raise awareness and involve different stakeholders, but there is a lack of decision-making bodies with a mandate to implement ocean sustainability instruments. Even authorities that are tasked with regulatory decision-making, like the International Seabed Authority (ISA)[85] or the International Maritime Organization (IMO)[86], do not make universal legislation and the effect of international legal instruments is limited to parties that have ratified or acceded to a particular treaty. Human interventions have global effects, whereas global governance strategies suffer from a lack of consensus between states and limited means of implementation and enforcement. In addition, it is not clear how and when (interdisciplinary) research enters the policymaking arena, who the actors are, what instruments are the most useful and at which level of governance they should act.

The UN Decade of Ocean Science for Sustainable Development exemplifies the need to involve science in ocean sustainability and governance. Generally, international decades, with their broad ambitions and wide range of activities, are criticized in diplomatic circles as being ineffective, both because of the lack of value they add to diplomacy and their lack of positive impacts on society at large. Against diplomatic scepticism, the Decade offers a concrete opportunity to showcase the value added by ocean science to society and, in fact, to international relations. A “science diplomacy” approach may very well be an opportunity to use science to further the building of capacities and to tackle common problems related to ocean sustainable development in the international realm. The Decade could be used by the global marine science powers, including the USA, Japan, China and Europe, to promote cooperation to tackle the challenges of the Anthropocene. For example, the Decade could be used to mobilize science and technology under a "Mission: Healthy Oceans, Seas, Coastal and Inland Waters.", whereby broad, but very ambitious, targets for action are identified, for example stopping new pollutants from entering the ocean and halving pollution in the ocean by 2030.

Credit: iStock

Fully integrating knowledge into decision support frameworks involving stakeholders is vital to govern ocean space properly.

[84] https://oceanconference.un.org/

[85] https://www.isa.org.jm/

[86] http://www.imo.org/en/Pages/Default.aspx

The European Union is negotiating the European research priorities for the next decade.

At the European level, the EU is currently negotiating whether to fund a Mission on Healthy Oceans, Seas, Coastal and Inland Waters within the context of the next Framework Programme for Research and Innovation. With a potentially staggering €1 billion budget over seven years, such a Mission would offer a vehicle to mobilize especially the EU but also international scientific resources. The European Marine Board will play an active role in promoting and implementing this initiative if funded. The EU initiative might motivate other states and regions to develop their own specific approaches, focusing attention and funding/investments. States will be motivated especially if they have opportunities to build capacity as well as being recognized or acknowledged as world leaders. At the very least the Decade can be used to build capacities in states with less advanced marine science capacities, specifically so that they can contribute to understanding and tackling ocean challenges.

While a Mission on Healthy Oceans, Seas, Coastal and Inland Waters may offer opportunities for linking science and policy communities, key questions remain, such as: What tools (e.g. marine spatial planning, integrated coastal zone management, networks of marine protected areas, environmental impact assessment) are most appropriate and for which purposes? On what levels do stakeholders, such as scientists, get involved and what is their influence? How do we safeguard high scientific standards for sustainable ocean governance? What balance should be struck between conducting more marine research to close knowledge gaps and using this research to govern our use of the ocean? The answers to these and other questions influence not only marine science in Europe, but open opportunities for capacity building in developing and emerging industrialized countries that struggle to find public investment for science.

7.2. Final comment

To achieve the ocean we need by 2030, marine science should be holistic and transdisciplinary, with the inclusion of sustainability science. A key priority is also the development of a business model that ensures the long-term economic sustainability of ocean observations developed through co-design with all stakeholders. Clever and motivated people are making all the difference and a good way to attract them to ocean science is to present clearly defined challenges. The advent of the hereditary molecules of DNA by Watson, Crick, Wilkins and Franklin is a good example of how a clearly defined scientific question drew highly motivated and clever researchers to address the same problem. Although the Ecosystem Approach and the Marine Strategy Framework Directive (MSFD) call for a "strategic" and "holistic" approach, ocean science suffers from a lack of clearly defined science frontiers that are generally rather loosely defined by individual researchers making most efforts small and fragmented. An example of a large and concerted endeavour is the efforts to monitor and provide advice on the size of commercial fish stocks for fisheries management in Northern Europe. Here up to 10 vessels from different countries perform surveys according to an agreed protocol and combine their results to estimate the size of fish stocks. There are a few other examples of similar efforts in developing ocean research to answer a difficult question or solve a complex tasks, such as the ARGO programme[87] and the international ocean model inter-comparison experiments. The UN Decade of Ocean Science for Sustainable Development challenges us to use the next decade to show what ocean science can do for sustainable development. There are many ways to implement this such as the proposal to more than double the amount of protein humanity obtains from the ocean from the current 2% to 4–5% by 2030 and thereby addressing the UN Sustainable Development Goal 2[88] (SDG 2, Zero Hunger). This can be achieved by promoting sustainable aquaculture and fisheries, but it has to be done within an ecosystem-based management framework to achieve SDG 14 on conserving and sustaining life below the water. There are therefore trade-offs to be made. The next generation of ocean research for sustainability must be based on sound natural science but must also deeply integrate the perspectives of ethics, humanities, social sciences, political sciences and law.

[87] http://www.argo.net/

[88] https://www.un.org/sustainabledevelopment/hunger/

7.3. Recommendations

We need to design research programmes addressing the following key knowledge gaps:

- The influence of climate change on the physico-chemical characteristics of the ocean including the interaction between the ocean and ice sheet melting and future long-term sea-level rise;
- The four dimensional ocean (spatial and temporal framework) and functional links between the components of the marine system, i.e. physics, chemistry, biology, ecology and humans;
- The impact of single and cumulative stressors (e.g. climate change, pollution, over-fishing) on the functioning of marine ecosystems, their interactions, evolution and adaptation over time, and the ecosystem services they provide;
- The characteristics, probability distribution and impacts of climate-related extreme events and geohazards (e.g. marine heat waves, meteotsunamis and submarine earthquakes, landslides, volcanic eruptions and their associated tsunamis) and their evolution under climate change; and
- Ocean technologies, modelling, data and artificial intelligence needed for sustainable ocean observations.

In addition, we recommend the following actions:

- Integrate the four dimensional structure and function of marine ecosystems into management and conservation practices;
- Establish an early-response system to gain a better understanding of the short- and long-term impacts of extreme hydrodynamic, climatic and geological events on biota and ecosystem services;
- Develop a business model that ensures the long-term economic sustainability of ocean observations that will involve co-design with all stakeholders. It should include biological observations and geological events, adaptive sampling and access to data in real-time;
- Underpin observations and experiments with an ensemble of validated quantitative physical, biogeochemical, biological, bio-economic and socioecological models that can quantify uncertainties and help develop early-warning indicators for multiple stressors or approaching tipping points;
- Develop the ocean Internet of Things by developing new technologies for use in the sea, allowing observations to be transferred in real time to satellites or other communication networks through enhanced local data processing including machine learning and artificial intelligence;
- Develop a virtual reality ocean platform where all information can be uploaded and visible to the public in real time;
- Promote dialogue across disciplines, and train future scientists to focus on a holistic vision of the marine ecosystem. This includes sustainability scientists working in parallel with scientists trained in traditional disciplines;
- Further develop marine citizen science as a tool for understanding the ocean as a common good whose health is crucial for humanity; and
- Set up a sustainability science forum, which includes industry and civil society partners.


Credit: Sheila Heymans

Epilogue

Imagine a future where we have achieved net zero global anthropogenic CO_2 emissions, limited global warming to 1.5°C above pre-industrial levels and implemented all the recommendations set forth in this document. The importance of the ocean has become clear to the public, not only as an asset that is nice to have, but also as an imperative for human health and welfare through the food and other direct benefits it provides humanity and also for the seemingly hidden benefits. The public therefore understands their role in protecting the ocean and have voted for a government that recognizes the ocean as a common good that has to be protected as such. Governments understand that the ocean observation system is as important as the financial system – seen as too important to fail – and therefore protects ocean observatories the way they protected banks in the global downturn of 2008–2009. Ocean observations are seen as so important that governments fund ocean observations as they fund other utilities.

This public understanding was achieved through better education, citizen science and ocean literacy, and a virtual ocean based on real, timely data of what is happening in the ocean. This virtual ocean enables people to dive into the sea and explore the ocean. The virtual ocean is based on a platform where all real-time and historical data are uploaded continuously and used to describe how our ocean really works. This means that, for example, when a research vessel makes new measurements of temperature, salinity and oxygen, or bacteria, plankton, fish and mammals, these data are uploaded in real time to the virtual ocean. This virtual ocean, with all the known information about the physics, chemistry, geology and biology of the ocean, is used to see what our ferry ride might be like tomorrow, whether going sailing would be a good idea, or whether eating shellfish from a particular area might give you paralytic shellfish poisoning. This virtual ocean is used for management purposes, such as is planned for the Marine Spatial Planning Challenge game. The virtual ocean is used by managers and the public at large, and the public hold the politicians accountable for decisions that they make, not just in fisheries management and marine spatial planning, but also regarding climate change emissions and the economy.

In this future, we will have a better understanding of the impact that the melting ice caps, pollutants, mining, etc. have on the physics and chemistry of the ocean. We will understand the cumulative impacts of all these stressors on biodiversity and the functioning of the ecosystems. We will have a better understanding of the seafloor processes that trigger geological hazards such as underwater earthquakes, volcanos, landslides, meteotsunamis as well as accurate hazard assessments and early warning systems to mitigate their effects. However, some parts of the ocean will still be unknown and there will be a need to highlight these. It will therefore be necessary to have an ensemble of background models predicting what kind of organisms and habitats are in different locations, and how any changes due to human use or climate change might affect each area. When new information is gathered, the models will be updated and predictions improved and there is a direct link between surveys and models, and between surveys and global visualizations immediately after a sample has been taken. In this wonderful new world, sustainability is at the core of the marine science agenda, and the public at large and all stakeholders are partners in its co-design to address the critical knowledge gaps. This has led to a fully integrated scientific assessment of resilience strategies, associated trade-offs and underlying ethical concepts for the ocean, which is incorporated in the decision support framework. **This is our vision for the role of marine science in developing a sustainable future for our planet by 2030 and beyond.**

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Glossary

Anthropocene – The current geological age in which human activities are having a dominant influence on climate and the environment.

Big data – Data sets so large or complex that traditional data processing applications are inadequate. These datasets must be analyzed computationally to reveal patterns, trends and associations

Biological pump – Refers to the capacity of living organisms to fix carbon from the air or water and keep it in that state for years, such as corals that use carbon in seawater to build their skeletons.

Broadband acoustics – A remote sensing method relying on a continuous range of frequencies of acoustic waves.

Chemosynthetic – Organisms that use chemical energy to produce food.

Citizen Science – The collaboration between citizens and scientists in order to collect, investigate, analyse and report data from the environment under the auspices of a scientific project.

Cobalt-rich ferromanganese crusts – These are formed by precipitation of metals dissolved in seawater on rock substrates of volcanic origin. They occupy large areas on top of seamounts, ridges and plateaus.

Dynamic time warping – An algorithm for measuring similarity between two temporal sequences in a time series analysis.

Ecosystem services – The services provided by the processes, functions and structure of the environment that directly or indirectly contribute to societal welfare, health and economic activities.

Eddies – Relatively small circular water currents running independently from the main current. They transport water and heat and promote large-scale mixing of the ocean.

Eutrophication – The process of nutrient enrichment in aquatic ecosystems causing the productivity of the system to cease to be limited by the availability of nutrients. This stimulates the growth of algae, ultimately resulting in depletion of oxygen. Nutrients can originate from agriculture, riverine input, municipal wastewaters, aquaculture or airborne loading.

Extirpation – The local extinction of a species in a particular geographic area.

Fuzzy Logic – A type of reasoning based on the recognition that statements are not only true or false but can also range from 'almost certain' to 'very unlikely'.

Gaussian emulators – A statistical model used for uncertainty quantification.

Gaussian mix model – A probabilistic model that assumes all data points are generated from a mixture of Gaussian distributions with unknown parameters.

Hybrid Markov models – These are stochastic models that model randomly changing systems, where it is assumed that the future state is only dependent on the current state not past states.

Hyperspectral imaging – A remote sensing method in which an imaging spectrometer collects hundreds of images at different electromagnetic wavelengths for the same spatial area allowing detailed spectral signatures to enable identification of specific materials.

Internet of Things (IoT) – Interconnection via the internet of computing devices embedded in objects connected to each other and enabling them to send and receive data.

Lab-on-a-chip – A device that integrates laboratory functions on miniaturized scale within a portable or handheld device.

Marine natural capital – The stock of natural assets the ocean provides from which humans derive ecosystem services.

Massive polymetallic sulphides – Mounds formed of metal sulphide mineral precipitates and hydrothermal vent debris. They are commonly found along tectonic plate boundaries and volcanic provinces.

Mesocosm – An outdoor experimental system examining the natural environment under controlled conditions, acting as a bridge between field and laboratory experiments.

Metabolomics – The study of small molecules resulting from metabolism present within cells, tissues or organism such as vitamins and lipids.

Meta-populations – Populations of populations linked by high connectivity rates.

Meteotsunami – Atmospherically generated shallow-water waves caused by a rapid change in Barometric pressure, which displaces water.

Mixed layer – The upper portion of the ocean's surface layer where air-sea exhanges cause the water to mix and become vertically uniform in temperature, salinity and density.

Multifactorial model – A model that incorporates more than one factor, such as temperature, salinity, wind, and topology in a physical model.

Ocean acidification – A reduction in the pH of the ocean caused by uptake of CO_2 from the atmosphere.

Ocean stratification – Separation of water with different properties (i.e. density, salinity, and temperature) into layers acting as a barrier to mixing.

Phenology – The timing of recurring biological events (e.g. seasonal migrations or spawning), the causes of their timing in relation to biotic and abiotic forces, and the interrelation among phases of the same or different species.

Phyla – A level of taxonomic rank based on morphological, developmental or evolutionary relatedness.

Phytoplankton – Microscopic algae that live in the water column.

Polymetallic nodules – Rock concentrations on the sea floor formed of concentric layers of iron and manganese hydroxides around a core. Also known as manganese nodules.

Probabilistic model –These incorporate random variables and probability distributions into a model of an event.

Proteomics – The study of the structure, function and interactions between proteins of a cell, tissue or organism.

Soft engineering – A shoreline management practice using ecological principles and practices that enhance habitats while providing stability, reducing erosion and ensuring shoreline safety.

Surrogate models – An engineering method where the outcomes cannot be easily measured, are expensive or time-consuming, so a model is used to predict outcomes.

Thermocline – The separation between a warmer water layer floating on a deeper and colder layer, resulting in stratification.

Thermohaline – The joint effect of temperature and salinity.

Transcriptomics – The study of the complete set of coding and non-coding RNA molecules produced by the genome under different biological conditions.

Underwater LIDAR (Light Detection and Ranging) imaging – A remote sensing method that uses pulsed laser light and a synchronized camera to produce a three-dimensional representation of observed objects.

Zooplankton – Small animals or immature stages of larger animals that live in the water column.

Abbreviations and Acronyms

ABNJ	Areas Beyond National Jurisdiction
AUV	Autonomous Underwater Vehicles
CEFs	Cells of Ecosystem Functioning
CO_2	Carbon dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DNA	Deoxyribonucleic Acid
EASAC	European Academies Science Advisory Council
EOOS	European Ocean Observing System
EU	European Union
EuroGOOS	European Global Ocean Observing System
EMB	European Marine Board
EMODnet	European Marine Observation and Data Network
EOV	Essential Ocean Variable
FAIR	Findable, Accessible, Interoperable and Reusable
FAO	Food and Agricultural Organisation of the United Nations
G7	Group of Seven (Canada, France, Germany, Italy, Japan, the UK, the USA)
GEOSS	Global Earth Observation System of Systems
GES	Good Environmental Status
GOOS	Global Ocean Observing System
GPS-A	Acoustic Global Positioning System
ICES	International Council for the Exploration of the Sea
IEA	Integrated Ecosystem Assessment
IOC-UNESCO	Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization
IMO	International Maritime Organization
IOT	Internet of Things
ISA	International Seabed Authority
JPI Oceans	Joint Programming Initiative Healthy and Productive Seas and Oceans
LMEs	Large Marine Ecosystems
MOC	Meridional Overturning Circulation
MSFD	Marine Strategy Framework Directive
OECD	Organisation for Economic Co-operation and Development
OHH	Oceans and Human Health
OSSE	Observing System Simulation Experiments
RNA	Ribonucleic Acid
ROV	Remotely Operated Vehicle
SDG	Sustainable Development Goal
SOCIB	Baleric Islands Coastal Observing and Forecasting System
UN	United Nations
USV	Unmanned Surface Vehicle

Annex 1

On 8–9 November 2017, the European Marine Board organized a foresight expert workshop at the Hotel Metropole in Brussels (Belgium) to discuss and decide on the high level content for their Navigating the Future V publication. The European Marine Board Secretariat, together with external facilitator Lizzie Crudgington (Bright Green Learning[88]), led the planning and organization of this workshop, including interaction with all experts to initiate the exchange of ideas, develop understanding of the Navigating the Future V process, and co-design a decision-making process for topic selection. The meeting was financially supported by the Flanders Marine Institute (VLIZ).

Credit: European Marine Board

Experts participants to the European Marine Board's Navigating the Future V Foresight Workshop at the Hotel Metropole in Brussels, November 2017.

The 19 experts were nominated by European Marine Board member organizations as leading European experts in the field of marine science and related disciplines, as well as being "blue-sky" thinkers. They were jointly tasked with taking a bird's-eye big-picture view of marine science and to look to the future (2030 and beyond) to identify key topics/themes that are set to significantly advance our understanding of the marine and broader Earth and climate systems, and that will be of increasing importance to societal well-being in the decades to come.

The selected experts were: Sukru Besiktepe (Dokuz Eylul University, Turkey), Ferdinando Boero (CoNISMa, Italy), Valerie Cummins (University College Cork, Ireland), Jan de Leeuw (NIOZ, the Netherlands), Carlos García Soto (IEO, Spain), Jeremy Gault (University College Cork, Ireland), Edward Hill (NOC, United Kingdom), Geir Huse (IMR, Norway), Colin Janssen (Ghent University, Belgium), Denis Lacroix (Ifremer, France), Francesca Malfatti (OGS, Italy), Jan Mees (FWO, Belgium), Luis Menezes Pinheiro (University of Aveiro, Portugal), David Paterson (MASTS, United Kingdom), Catherina Philippart (NIOZ, the Netherlands), Ralph Schneider (KDM, Germany), Anne-Marie Tréguier (IUEM, France), Sybille van den Hove (Bridging for Sustainability, Belgium), Jan Marcin Węsławski (IO PAN, Poland).

[88] https://brightgreenlearning.com/

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