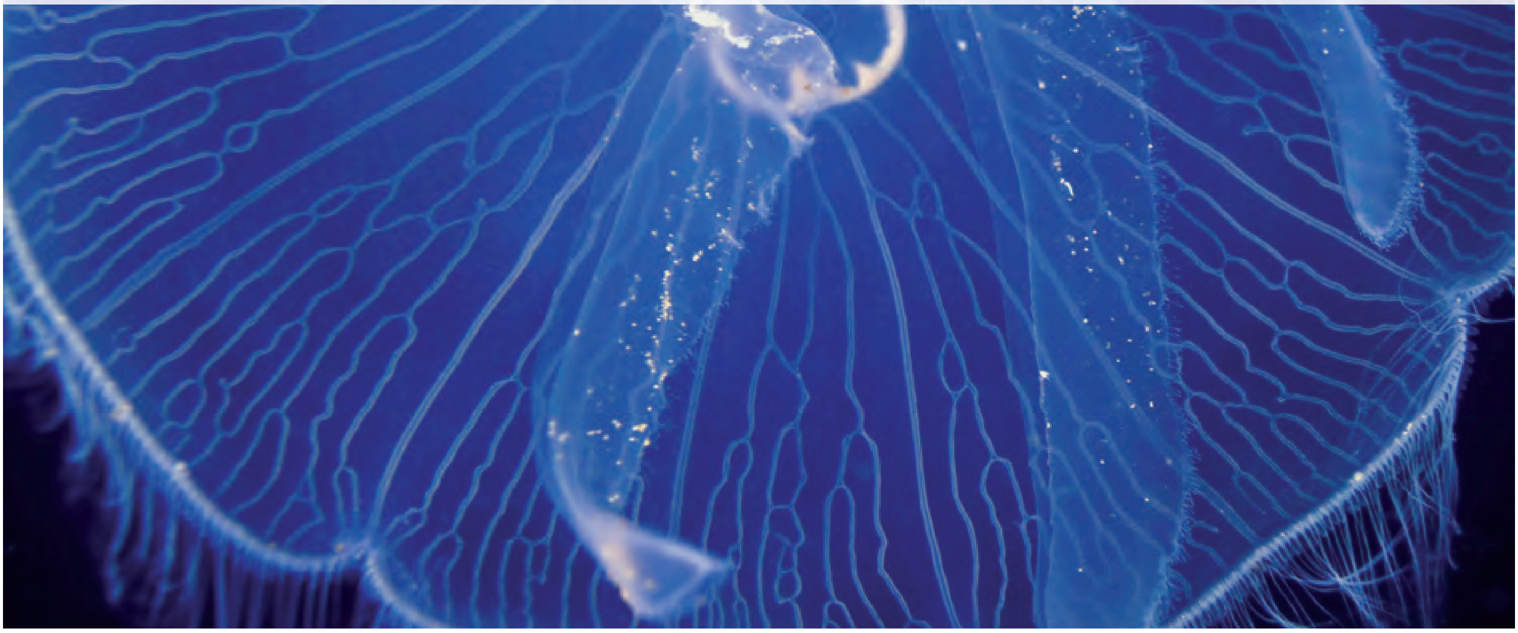
EUROPEAN SCIENCE FOUNDATION

Sailing through Changing Oceans:
Ocean and Polar Life and Environmental Sciences on a Warming Planet

Science Position Paper



European Science Foundation (ESF)

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ISBN: 978-2-36873-014-0

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Foreword

The European Science Foundation (ESF) Science Position Paper *Sailing through Changing Oceans* has experienced a long journey, originating from a meeting held in 2011 in Cascais, Portugal. At this venue, organised under the auspices of the ESF's Standing Committee for Life, Earth and Environmental Sciences (LESC), now Scientific Review Group for Life, Earth and Environmental Sciences (SRG-LEE), a panel of scientists involved in the ESF European Collaborative Research Programmes EuroDIVERSITY, EuroMARC and EuroDEEP joined other scientific experts involved in the international programmes *Antarctic geological drilling* (ANDRILL), *Life in Extreme Environments* (CAREX), *The Commission for the Conservation of Antarctic Marine Living Resources* (CCAMLR), *Evolution and Biodiversity in the Antarctic* (EBA) and *Integrated Marine Biogeochemistry and Ecosystem Research* (IMBER). The Executive Secretary of the *European Polar Board* (EPB) also attended the meeting.

Coordinated by the European Science Foundation, the experts initiated a discussion on the theme of ocean and polar life and environmental sciences on a warming planet, exploring long-term and widely multidisciplinary collaborative opportunities in view of common and/or complementary top-priority future research needs in marine and polar areas: the valuable and synergetic work of the group led to the decision, a few months later, to integrate all the outputs of the discussion, including a number of scientific essays, into a dedicated European Science Foundation Science Position Paper.

The rapidly evolving European scenario for research in oceanic and polar regions within a warming planet scenario has prompted the authors not only to analyse the evolution of this scientific domain in the last 50 years and to identify the key and most pressing priorities for future research, but also to carefully analyse the recommendations made by international organisations and scientific clusters during the development of the European Commission Horizon 2020 Work Programme. The final part of the Science Position Paper provides the reader with an analysis of the past and potential future opportunities to develop research in cutting-edge priorities in ocean and polar life linked to the warming of the planet under the Horizon 2020 umbrella, thus generating opportunities for new synergies among experts on climatic change, polar regions, ocean processes, marine ecosystems and biodiversity on a European and a global scale.

Sailing through Changing Oceans looks at key topics of the future of research on ocean and polar sciences in a warming planet, in the framework of the new European research perspective and of its link to the increasing societal needs for a sustainable economy. Recognising the fundamental importance of the indications provided by the UN Conference on Sustainable Development Rio+20 and of the related sustainable development goals, *Sailing through Changing Oceans* advocates for a key concept, which brings together societal and research needs: '*In the current context of global change, sustainable and responsible exploitation of the oceans can be realised only through a deep understanding of the ocean processes and of the associated ecosystems spanning every latitude of Planet Earth.*'

Professor Dr Reinhart Ceulemans
Chair of the ESF Scientific Review Group for Life, Earth and Environmental Sciences, SRG-LEE

Dr Paola Campus
ESF Senior Science Officer in charge of the Scientific Review Group for Life, Earth and Environmental Sciences

Dr Roberto Azzolini
National Research Council of Italy (CNR), Department of Earth System Science and Environmental Technologies

Foreword

This report is very timely.

Indeed, concerning the two major environmental challenges we are facing today, that is the impact of climate changes and the preservation of biodiversity, the polar regions are of very particular scientific interest. The jeopardised future of the polar bear with the reduction in the extent of Arctic sea ice is already well known. Yet, with a region in Siberia, the region around the US Palmer Antarctic station in the western Antarctic Peninsula is the other part of our planet where the increase in mean temperatures is the most important. As a result, about 70% of some populations of Adélie penguins there have already disappeared. Even on the main part of the Antarctic continent, the modelling of the populations of the iconic emperor penguin suggest that according to the last IPCC scenarios they will become extinct in one or two centuries. Climate warming also results in invasive species establishing and competing with endemic species such as common flies in the sub-Antarctic Kerguelen Archipelago.

However, considering biodiversity, the alarming decline obviously does not only result from climate change as overfishing may superimpose on the effect of warming. It is particularly so in Arctic seas and the future of cod populations remains a major issue. With some exceptions, the Southern Ocean has been essentially preserved since the periods of the massive destruction of seals and whales. Yet, an analysis of the impact of climate variability and long-term change is essential to determine the conditions for potential fisheries to be sustainable and allow for the preservation of biodiversity.

But there is also great scientific interest in investigating the biodiversity of the Arctic and Antarctic regions for basic research. Deciphering, for example, the phylogeny of fish of high latitudes with molecular biology tools enables a remarkable insight into the evolution of fish. Basic research can even contribute to biomedical and biotechnological applications, such as with enzymes which are still active at low temperatures or with antimicrobial and antifungal molecules.

With such important scientific challenges, we have to think of how our scientific communities can be organised to be efficient. Why should biologists not be able to reunite their forces at the international level, and particularly by bringing together European resources, as physicists have been doing for years in particle physics! Clearly, by working together under the umbrella of the European Polar Board and the European Union, all the managers of European polar programmes could facilitate the achievement of the best science.

Indeed again, this report is very timely as it parallels important international initiatives such as the SCAR horizon scan and the Belmont Forum Collaborative Research Action. Yet, we also need to make sure that, under the frame of the main scientific questions which emerge from communities, there is still a road for a bottom-up development of innovative individual initiatives.

Professor Yvon Le Maho
Director of Research, French National Centre for Scientific Research (CNRS)
Emeritus Member, French Academy of Sciences

I am very pleased that the European Science Foundation has been able to coordinate and support the meeting in Cascais, which generated a valuable synergy among a number of EUROCORES Project Leaders and experts of international programmes, resulting in the development of this publication.

The Science Position Paper is very timely, considering the forthcoming new Work Programmes of Horizon 2020, and addresses key issues related to ocean and polar life and environment in a warming planet through the contributions from a range of experts, integrating in the final analysis the recommendations of the major stakeholders in marine and polar sciences.

The Science Position Paper is not only aligned with the societal element and message of the ESF-COST publication *RESCUE: Responses to Environmental and Societal Challenges for our Unstable Earth*, but it further elaborates concepts related to the sustainable development goals endorsed at the Rio+20 – United Nations Conference on Sustainable Development, and highlights priorities linking research and sustainable development needs related to oceans and polar areas.

I concur with the vision on synergies in Polar Regions proposed by Professor Le Maho and I would like to add that a joint action of the European Polar Board, the European Marine Board and the European Union would be very beneficial to the development of research on ocean and polar life on a warming planet.

I have no doubt that this paper will be of interest to a large number of stakeholders and will generate opportunities for improved collaboration as well as concerted actions in the future.

Martin Hynes
ESF Chief Executive

Executive Summary

Sailing through Changing Oceans: Ocean and Polar Life and Environmental Sciences on a Warming Planet

J.P. Henriet, L. De Santis, E. Ramirez-Llodra, R. Azzolini, P. Campus

In the current context of global change, sustainable and responsible exploitation of the oceans can be realised only through a deep understanding of the ocean processes and of the associated ecosystems spanning every latitude of Planet Earth.

This publication originates from a meeting, held in 2011 in Cascais, Portugal, where a panel of scientists involved in a number of European Collaborative Research Programmes (EUROCORES) of the European Science Foundation (ESF) joined other scientific experts involved in international programmes. The group of experts (named the Cascais Group) initiated a discussion on the theme of ocean and polar life and environmental sciences on a warming planet, exploring long-term and widely multidisciplinary collaborative opportunities with a view to identifying common or complementary top-priority future research needs in marine and polar areas.

The experts agreed on further developing their discussion and analysis though a publication produced under the auspices of the European Science Foundation: the Science Position Paper *Sailing through Changing Oceans: Ocean and Polar Life and Environmental Sciences on a Warming Planet.*

Moving across space, from Antarctica to the Arctic through the Atlantic, an analysis of the long-term, mid-term and short-term climatic changes is presented and associated to the description of a number of key processes and impacts which highly affect ecosystems and need to be carefully addressed in the future.

The science position paper is developed in four chapters.

Chapter 1 is a scientific and historical excursus which sets the framework for the science position paper. Jean-Pierre Henriet provides a synthesis of the major milestones, from the late 20th century to nowadays, related to climate variability and climate change, oceans and poles and to the Grand Challenges associated to these themes. Chapter 1 addresses the fast rise of interest in climate variability and climate change, of oceans and poles, and the consequent action of the European Committee on Ocean and Polar Sciences (ECOPS) in launching the Grand Challenges in Ocean and Polar Sciences. Furthermore, Chapter 1 addresses earth climate evolution at different scales, ranging from deep time, through ocean and ice shelf drilling, to recent times through seabed and ice coring. The rise of collaborative global studies in ecosystems, biodiversity and biogeochemistry, including the Marine Science and Technology (MAST) era, are addressed as well. Chapter 1 also provides an insight into the near future and a discussion on human resources and infrastructure for European ocean and polar sciences.

Chapter 2 addresses the main priorities and open scientific questions related to the dynamics of the oceans and polar environments in a warming planet. Five scientific reports are presented, highlighting a number of key messages and priorities, related to:

- Long-term climatic changes
- Super warm interglacials in the Pleistocene record
- Abrupt climate changes
- Sea level rise and the stability of ice sheets, from the geological perspective
- Past and potential future effects on the oxygenation level for vulnerable European basins: Baltic, Black, and Mediterranean Sea.

Fabio Florindo and Stephen Pekar highlight how geological records provide a backdrop which helps us understand the relationships between climate changes and carbon cycling today. Periods of high concentration of greenhouse gases and global temperatures in the past provide examples of how the Earth operated under such a climate. The collection (through ocean, land and ice-based drilling programmes) and exploitation of geological archives are, therefore, two key elements to assess the environmental changes observed nowadays and to project them in the future.

Dick Kroon concurs with the main conclusions of Fabio Florindo and Stephen Pekar and indicates the use of sediment cores combined with model simulations as a robust instrument to investigate causes and effects of climate warming in the North Atlantic and in the Arctic.

In line with the previous authors, Dierk Hebbeln looks with great interest to a global database collecting information on past abrupt climate changes and puts high on the research agenda the collection and analyses of marine sedimentary and coral records.

Laura De Santis discusses how peri-Antarctic drilling could reveal the way ice sheets behaved in past periods of high temperature and high atmospheric CO_2 content. She also highlights the contribution of peri-Antarctic drilling in the process of understanding how grounded ice responded to warming oceanic waters and to what extent the large freshwater discharges in a warming climate impacted sea level and the thermohaline circulation.

Gert De Lange highlights how some of the ocean sub-basins, ranking among the most vulnerable on Earth, are within the European realm: the Baltic, the Mediterranean and the Black Sea. These seas have impacted in different ways climate zones and environmental conditions: thus the three seas offer a unique opportunity for conducting integrated studies on any change (with special focus on oxygenation levels) which might impact their equilibrium, the biodiversity and the human use of the seas (including fisheries and recreation).

Chapter 3 addresses the main priorities and open scientific questions related to the dynamics of ecosystems under global change.
Five scientific reports are presented, highlighting a number of key messages and priorities, related to:

- Deep-sea biodiversity dynamics and ecosystem stability
- Ecosystem connectivity in a changing ocean
- Deep-sea biodiversity, ecosystem function and ecosystem services in our changing planet
- The response of reef framework-forming cold-water corals to ocean acidification.
- Stresses on polar marine ecosystems: impact on key ecosystem functions and services

Nadine Le Bris highlights the importance of habitats, species and gene diversity in deep-sea systems. Extreme environments provide unique natural models to understand the mechanisms which establish and maintain biodiversity in deep-sea ecosystems. Key issues to be addressed to progress in the understanding of deep-sea habitats include the relationship between energy sources and biodiversity, the role of engineer species, recruitment dynamics and growth rates and the response to disturbances.

Marina Cunha discusses the fundamental aspects of deep-sea biodiversity and ecosystem function in relation to our changing planet: the understanding of habitats, species, gene diversity of deep-sea systems and ecosystem connectivity in the oceans will help determine the effects of climate change and/or human exploitation on marine ecosystems.

Eva Ramirez-Llodra and Maria Baker describe the unique attributes of deep-sea ecosystems and the services they provide, engaging the reader in an overview and discussion of current impacts faced by one of the last pristine biomes in Planet Ocean. The increasing use of deep-sea services, ocean acidification and climate change impact ecosystems and biodiversity. The authors indicate it is imperative to continue to explore and study deep-sea environments using interdisciplinary and ecological approaches.

Murray Roberts highlights how acidification caused by increasing anthropogenic CO_2 affects the oceans by inducing a decline of sea water pH and substantial modifications in cold-water corals. The author recommends developing long-term experiments to assess the effects of temperature changes, ocean acidification and multiple stressors on marine ecosystems.

In the final essay of Chapter 3, Cinzia Verde, Guido di Prisco, Melody Clark, Lloyd Peck and Federico Lauro highlight the vulnerability of polar ecosystems and focus on the potential cumulative effects of climate change on organism physiology, populations of individual species, community composition and biodiversity. The authors propose as a priority a set of key questions to address the impact of stressors on key ecosystem functions and services of polar marine ecosystems.

Chapter 4 projects the priorities identified in Chapters 2 and 3 into the new European research scenario characterised by the EU Framework Programme for Research and Innovation Horizon 2020.

In the first part, Paola Campus and Roberto Azzolini provide a synthesis of the publications, principal conclusions and recommendations of the major scientific clusters and international organisations in the scientific areas covered by the science position paper *Sailing through Changing Oceans*. Going through a summary of publications produced between 2011 and 2014 and addressing marine and polar topics linked to climate change, life and environment, the authors highlight how some of these publications specifically aimed at influencing the forthcoming Horizon 2020 calls, while some others (in particular those linked to international organisations) used a more general approach to highlight the main societal needs for achieving sustainable development, respectful of the environment.

Priorities highlighted by the Climate Change and European Marine Ecosystem Research (CLAMER), the EC Marine Strategy Framework Directive (MSFD, 2008/56/EC), the Joint Programming Initiative Healthy and Productive Seas and Oceans (JPI Oceans), the European Marine Board, the UN Conference on Sustainable Development (Rio+20), the International Atomic Energy Agency (IAEA) and the European Polar Board have been taken into consideration. Noting that such priorities refer to phenomena on a global scale, often including polar areas (e.g., sea level rise, changes in marine ecosystems, climate change and ocean acidification), but not necessarily covering all the key challenges associated with these extreme regions (e.g., permafrost, ice melting, recent climate change and adaptation of marine organisms), the authors present a comparison of such priorities with the research priorities indicated in Chapters 2 and 3.

In the second part of Chapter 4 Paola Campus and Roberto Azzolini analyse the calls of the first Horizon 2020 Work Programme 2014-2015 related to ocean and polar life and environmental sciences on a warming planet.

The areas of opportunities generated for the priorities listed in Chapters 2 and 3 are discussed both on a global scale and on a polar scale. Next, the authors highlight which research priorities listed in Chapters 2 and 3 are still in need of finding a niche in the second and third run of calls of the forthcoming Horizon 2020 Work Programmes, aiming to stimulate the scientific community to become proactive with the relevant stakeholders in order to cover the still existing gaps.

Sailing through Changing Oceans aims to generate new synergies among experts on ocean and polar life and environmental sciences on a warming planet in the current European and global funding scenario.

Chapter 1

The Road to Climate Change Research: Life and Environment in Ocean and Polar Sciences

Jean-Pierre Henriet – Laura De Santis

Of climate variability and climate change, of oceans and poles, and Grand Challenges

By the late 20th century, the topic of 'Climate Change' had moved into the foreground, impacting on both society and science. When assessing climate change, both in a scientific and societal context, it is important to remain aware of two competing processes in the observational record and in any reasonable scenario of expected future climate evolution (von Storch and Hasselmann 1996): in the coupled ocean-atmosphere-biosphere-climate system, 'climate change' and 'climate variability' have similar signatures, namely low-frequency climatic modifications, and are therefore sometimes confused.

- 'Climate variability' arises from natural mechanisms unrelated to Man's actions. A distinction should be made between *external* and *internal* natural variability. Major *external* controls result from orbital periodicities (the 'Milankovitch' cycles), from variations of the energy output of the sun and from shielding of the atmosphere mainly by volcanic ash. *Internal variability* arises from (a) non-linear interactions yielding multiple equilibria, and (b) the accumulation of short time-scale 'weather noise'. A relevant example of non-linear dynamics yielding multiple equilibria is linked to the North Atlantic Ocean circulation, in particular in its relation to North Atlantic overturning.
- 'Climate change' (written in this essay as 'Climate Change' when viewed from a societal perspective) is reserved to denote the formation of persistent climatic anomalies which are related to the activities of Man. Examples of drivers are urbanisation, deforestation and desertification, and anthropogenic emissions of greenhouse gases, aerosols and soot.

In both climate variability and climate change, the oceans and the poles jointly take a central position, for two reasons in particular:

a. the ocean realm is the main storage and re-distributor of heat on our planet and it hosts vital but vulnerable resources of food and energy, and
b. the polar environment consorts with ocean dynamics, and by its sensitivity it provides early warning of any change.

Both environments have, moreover, remarkably built – in sediments and ice – a parallel archive of climate variability and climate change, of instructive reading and confrontation.

In the preface to what can perhaps be identified as the first European position paper on ocean and polar research (Wainwright Ed. 1991, Figure 1.1), Professor Umberto Colombo, President of the European Science Foundation (ESF), and Professor Paulo Fasella, Director-General for Science, Research and Development at the Commission of the European Communities (EC DG XII), stated that, by their very nature, the oceans and Polar regions call for cooperation in research, and placed the development of a long-term European strategy in marine and polar research high on the agenda.

In early 1990, EC DG XII and ESF established together a European Committee on Ocean and Polar Sciences (ECOPS). ECOPS prepared a

Figure 1.1.
The Ocean and the Poles (Wainwright Ed. 1991).

series of European Research Conferences on various themes at the frontiers of marine and polar sciences that were recognised as of particular interest for Europe. The outcome of these European Research Conferences was reviewed by a major policy conference that attracted scientists, engineers and policy makers from all over Europe and beyond: the **European Conference on Grand Challenges in Ocean and Polar Science,** organised in Bremen in September 1994 (Hempel 1996, Figure 1.2).

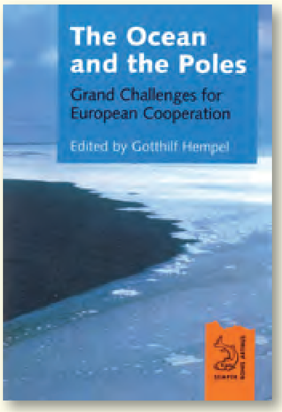

Figure 1.2.
Proceedings of the Grand Challenges in Ocean and Polar Science, Bremen 1994 (Hempel 1996).

Long before 1990, a number of initiatives of internationally organised collaborative programmes for the study of the oceans and the poles and for the shaping of a sound governance of the ocean's resources had sprung up in Europe. Karl Weyprecht drafted the outline of the International Polar Years in 1875. Otto Pettersson moved the creation of the International Council for the Exploration of the Sea (ICES) in Copenhagen in 1902. One year later, Prince Albert of Monaco chaired the launching of the General Bathymetric Chart of the Oceans (GEBCO) in Wiesbaden. The festive opening of the monumental *Musée Océanographique* in Monaco, in March 1910, was followed by the launching of the *Commission Internationale pour l'Exploration Scientifique de la Mer Méditerranée* (CIESM) the very next day.

The Grand Challenges presented in Bremen in 1994 were defined as four major long-term projects for European cooperation. They were announced in ESF Communications nº 28 (April 1993) and in the second edition of the brochure *The Ocean and the Poles* (September 1993). Before that, they had been submitted as draft proposals to the heads of the ESF and EC DG XII for consideration in the EC 4th Framework Programme (FP4, Marine Science and Technology programme MAST 3 and ENVIRONMENT programmes). All four Grand Challenges were considered for a period of 6-10 years and a budget of over 50 MECU each. The four Grand Challenges and their promoters were (Hempel 1996):

- Operational Forecasting of the Oceans and Coastal Seas (J. Woods and W. de Ruijter)
- Variability of the Deep Sea Floor (X. Le Pichon)
- The Arctic Ocean (O. Johannessen)
- European Programme on Ice Coring in Antarctica (EPICA) (C. Lorius).

The operational forecasting of the oceans and coastal seas was concretised in the founding of EuroGOOS (European Global Ocean Observation System) in 1994. It grew into an association of agencies to further the goals of operational oceanography under GOOS in the European seas, counting today some 34 members from 17 EU Countries and actively organising conferences. The three other Grand Challenges would contribute in a major way to our fundamental insights into ocean and polar science in a context of Climate Change.

Prelude to the ECOPS Grand Challenges in Ocean and Polar Sciences

The 1994 Grand Challenges did not come out of the blue. When the heads of Directorate XII of the European Commission and of ESF met in 1990 to create jointly a European Committee on Ocean and Polar Sciences (ECOPS), they clearly had in mind to put Europe back on the map of global ocean and polar science, through cooperation.

The leaders of the Grand Challenges were all 'Captains of Science', high-profile scientists who had taken major responsibilities at institutional level in their country and internationally, and who yearned for more, for bigger. Gotthilf Hempel, for instance, was the first director of the Alfred-Wegener-Institute for Polar and Marine Research, founded in 1980 in Bremerhaven, and he held that position from 1981 to 1992. John Woods was Director of Marine Science for NERC from 1986 to 1994. Part of Woods' vision was global oceanography. The World Ocean Circulation Experiment (WOCE) had been planned during the 1980s and a bid was made for the UK to play a major role (Laughton et al. 2010). Ola M. Johannessen (NERSC, Bergen) had just launched in 1992 the Nansen International Environmental and Remote Sensing Center (NIERSC) in St Petersburg, exemplifying the opening of cooperation with Russia. Xavier Le Pichon had contributed to the rise of the theory of plate tectonics in the US, before becoming in 1969 the director of the Marine Geoscience department at the *Centre Océanologique de Bretagne* (COB) in Brest, under CNEXO. The merger of CNEXO – the *Centre National d'Exploration des Océans* – and the fisheries institution ISTPM in 1984 had meanwhile given shape to IFREMER, soon to become a key player in global ocean science and technology.

But the challenge was grand indeed. After the pioneering work of the early 20th century evoked earlier, European ocean science, and in particular the dynamic oceanography which had come to an extraordinary level of development in Scandinavia at the turn of the century before finding a first foster home in Germany in the 1920s, migrated to the US in the later *interbellum*. *The Oceans*, the 1,100 pages thick magisterial treatise which for decades would be the definitive source book in biological, chemical, geological and physical oceanography, was written in the US, with a Scandinavian pen: Harald Sverdrup wrote it jointly with his US colleagues Martin Johnson and Richard Fleming (Sverdrup et al. 1942), shortly after he had taken the helm at Scripps Institution of Oceanography in 1936. Strengthened by wartime naval research, US oceanographic institutions would soon move – only rivaled by Russian colleagues – into the driver's seat of postwar global ocean and polar research programmes, from the 1950s (the International Geophysical Year of 1957-58 included) until well into the 1970s. In palaeoclimate technology, Russia had moved to the forefront in deep ice coring. The team of Claude Lorius from St Martin d'Hères, France, who would pilot EPICA, had built fame by already untangling a first 160,000-year record of atmospheric CO_2 in the Russian Vostok Ice Core, Antarctica (Barnola et al., 1987).

Europe was awakening in the late 1980s, emerging from a relatively short but painful economic crisis. It was the European Science Foundation (ESF) that would pave the way to European collaboration in ocean and polar science. At its founding in 1974 in Strasbourg, ESF was not much more than a contact forum where officers from European research councils exchanged experience and protocols in science management. Soon, some seed funds were pooled from national resources for the organisation of international research conferences and for exploratory networking across national boundaries. In ocean and polar environmental and life sciences, ESF's early networks ECOD, EPOS, PONAM and GRIP, launched between 1986 and 1990, would broaden transnational access to large infrastructures such as vessels and drilling tools. These networks would become the cradle of the 1994 Grand Challenges (Figure 1.3).

Only the sizable resources of the European Commission, however, could foster some level of stability in transnational access to large infrastructures. Thirteen years after the creation of ESF, in 1987, the European Single Act, the first major revision of the 1957 Treaty of Rome, had set the European single market as a target for 1992. By the same token, science became a Community responsibility. This context clarifies the steady intertwining of science and economic considerations in EC programmes: for the EC, science is part of a strategy of economic development. From 1987 onwards and for more than 20 years, the subtle balance of cooperation and competition between bottom-up, broadband, curiosity-driven science with a global vision embodied by ESF, and top-down, policy-driven science supported by the EC for strengthening the economic interests of the European Union, would give an unprecedented boost to European science and technology.

This boost was timely: on a background of collapse of the former Soviet Union, the perspective of growth of the single market had sparked the ambitions for a more global role for Europe. Moreover, the period between 1986 and 1990 saw a remarkable global mobilisation towards ocean and polar science, which had no equivalent since the International Geophysical Year of 1957-58. The birth of the World Wide Web in 1989 came no doubt in support of global communication and collaboration. The World Ocean Circulation Experiment (WOCE, 1990-98) was to be the first truly global-scale investigation of the role of the oceans in climate. The International Geosphere-Biosphere Program (IGBP) was founded in 1986 and the Joint Global Ocean Flux Study (JGOFS), launched in 1987, would clarify how ocean biological processes responded to Climate Change. As to IPCC, launched in 1988, it would soon confront Man with an inconvenient truth.

Some major phases in this development are discussed below. For obvious reasons, this overview cannot be complete. It focuses on two questions, clarified further under the heading of the Cascais Initiative:

- What can we learn from past Climate Changes, documented in marine sediments and ice cores?
- How will Climate Change impact on ecosystems, biodiversity and ecosystem services, in the deep sea and in polar seas?

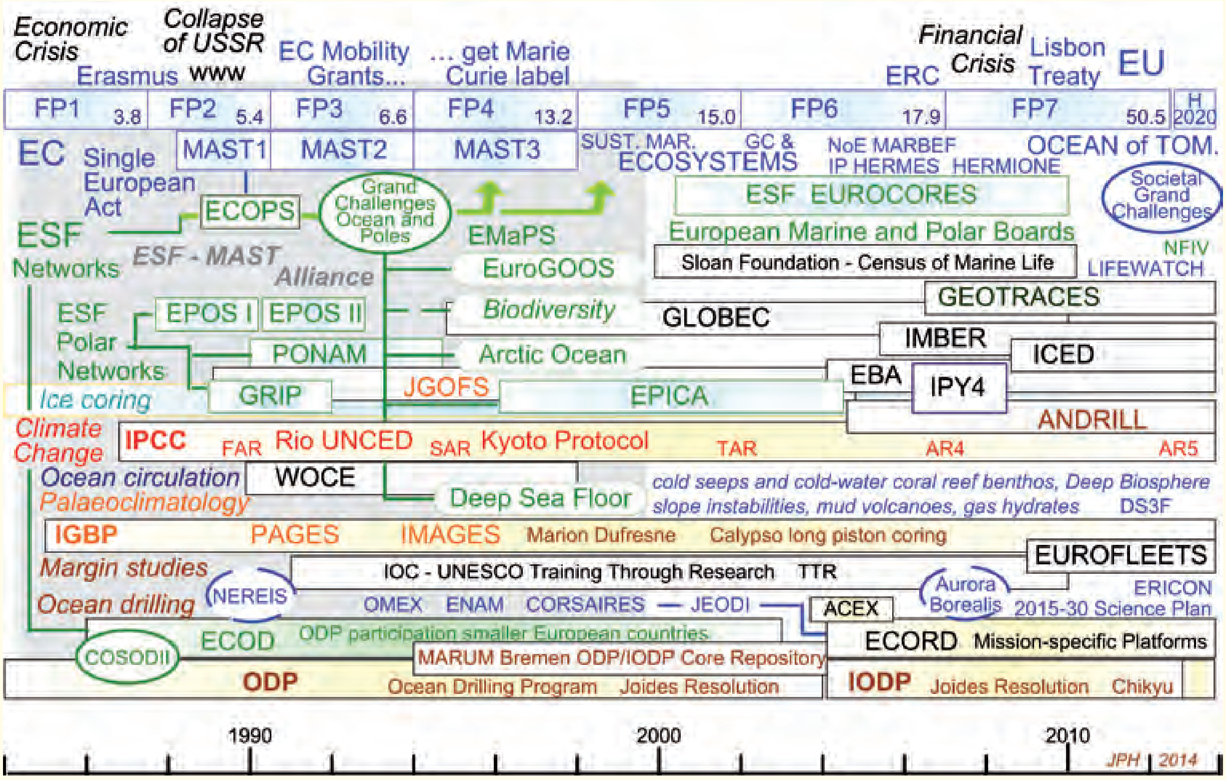

Figure 1.3. Architecture and roadmap of collaborative ocean and polar science in a Climate Change perspective, from the ESF-MAST Alliance times that bred the ECOPS Grand Challenges, to the Societal Grand Challenges of Horizon 2020 (figures added to the EC Framework Programmes are the total budget, in billion €).

Peering into the climates of deep time: ocean and ice shelf drilling

As soon as the Deep Sea Drilling Project (DSDP) had started its operations in 1967 on board of *Glomar Challenger*, month by month its discoveries revolutionised our ideas about Earth's ocean and climate history: the youth of the ocean basins, the drying up of the Mediterranean, the overall Cenozoic cooling trend revealed by oxygen isotopes, etc. In addition, cores recovered from the South Atlantic provided convincing support to the still infant plate tectonic hypothesis.

Quite a few European scientists had informally joined DSDP cruises upon invitation from US colleagues. In the years 1972-74, plans were made for internationalisation: DSDP moved in 1975 into its International Phase of Ocean Drilling (IPOD). Some veterans believe now they should have copyrighted the acronym. The partners France, USSR, Germany, United Kingdom and Japan each contributed an equal sum, while NSF contributed two-thirds of the funding, thereby retaining ultimate control.

When the end of DSDP (1983) was in sight, the Carter administration first considered a US Ocean Margin Drilling (OMD) initiative as successor: an academia-industry programme, to explore the petroleum potential of the US continental margin (Hay 2013). When none of the targeted partners proved enthusiastic – for varying reasons – a Conference on Scientific Ocean Drilling (COSOD) was convened in 1981 in Austin, Texas, to draft the outline of a new, international Ocean Drilling Program (ODP). The vessel would become the *JOIDES Resolution*. The considered term was 20 years, from 1983 to 2003 – a declaration of intent Europeans currently can only dream of. The Russian partner having meanwhile been excluded by the Reagan administration, there was a financial gap, and an opportunity for the smaller European Countries to move in, to join France, Germany and the United Kingdom. The ESF Network ECOD (European Science Foundation Consortium for Ocean Drilling) was readily forged, with Belgium, Denmark, Finland, Iceland, Ireland, Italy, The Netherlands, Norway, Portugal, Spain, Sweden and Switzerland being members. A second Conference on Scientific Ocean Drilling (COSOD II) was attracted to Strasbourg in 1987, within the scheme of ESF conferences. The proceedings, which highlighted the first successes of ocean drilling, set the stage of well documented position documents, readily usable as handouts in higher education.

But ambition was in the air. Yves Lancelot from CEREGE, close to Marseille, who had enthusiastically sailed on *Glomar Challenger*, proposed to

IFREMER the design of a European drilling vessel 'light': *NEREIS*. The concept was visionary: a flexible, multi-purpose vessel with removable rig, capable of drilling in water depths confined to 6,000 m – a choice allowing relatively reasonable dimensions and operational costs. *NEREIS* could readily turn into a platform for the deployment and recovery of automated vehicles and seabed observatories, through the sizable moon pool. A *NEREIS* Conference organised with EC MAST support in Brussels in 1990 attracted a vast and thrilled scientific audience. Nick Shackleton (Cambridge) chaired the palaeoceanography panel, which generated a convincing recommendation. Alas, while *NEREIS* was depicted as an ideal companion to *Joides Resolution*, quite a few supporters of ODP rather identified her as a competitor, and they fiercely combated the 'French ship'. After several years of vain efforts to rally broad European support, the project was discontinued. *NEREIS* had in many aspects been conceived ahead of her time, on the wrong continent.

The ECOD scheme under ESF, however, operated smoothly. Soon, the power of proposal of European scientists involved in ocean drilling science, supported in their exploratory efforts by MAST and national funding, significantly amplified. Sites urging for groundtruthing multiplied along the European margins, as evidenced in the preparatory meetings of the Bremen Grand Challenge Conference. European proposals dealing with palaeoceanography and palaeoclimatology, geofluids and Geosphere-Biosphere coupling processes, slope instabilities, polar margin evolution, etc. were piling up in the ODP system.

At the Bremen Grand Challenge Conference, the plan was phrased to meet the rising demand in a flexible way by *ad hoc* chartering of a geotechnical drilling vessel. A pilot exercise, based on an open call for letters of intent, documented a possible scenario comprising two multi-project sweeps along the European margins: an Atlantic leg and a Mediterranean leg. The FP4 coordination action CORSAIRES would not straightforwardly obtain the EC funds for chartering a vessel, but it was able to promote in international conferences and workshops the concept of science drilling with mission-specific platforms, as well as some novel scientific themes and relevant technologies.

The concept of mission-specific platform operations, as a European strategy within ODP, further ripened within the FP5 project JEODI (Joint European Ocean Drilling Initiative). Efforts to raise substantial long-term EC support for the participation of European teams in ODP under EC Art. 185 proved vain. Mission-specific platform drilling was finally concretised in 2004 as core business of ECORD (European Consortium for Ocean Research Drilling) – the European component of the Integrated Ocean Drilling Program (IODP). Europe's position in ocean drilling science had meanwhile been further strengthened by the opening of the MARUM ODP Core Repository in Bremen in 1994, which would soon act as a hub for core research and science training (summer schools).

ECORD started with *panache*: in an impressive exercise of operational coordination and ice management, project ACEX (Arctic Coring Expedition) mobilised in August 2004 three icebreakers – the *Vidar Viking* (with a purpose-built drill rig), the *Oden* and the *Sovetskiy Soyuz* – to drill the Lomonosov ridge at barely 250 km from the North Pole, in heavy sea ice. Five drill holes unveiled the Arctic's role in the development of the Palaeogene greenhouse, some 40 to 60 million years ago (Figure 2.1), and the Neogene icehouse, which we entered some 12 million years ago. In 2013, Russia would move back into the international ocean drilling community, as member of ECORD.

As a counterpart in the Antarctic, the ANDRILL project tracks the earliest glacial history of the Antarctic continent. No icebreakers are required there: the drill rig is built on the ice shelf. ANDRILL builds upon the successes of the McMurdo Ice Shelf Project (2006-07) and the Southern McMurdo Sound Project (2007-08). Two new drillings are planned in 2016-18 on the seaward edge of the Ross Ice Shelf, to further document the Palaeogene to Lower Miocene history of Antarctica, between some 65 million and 15 million years ago.

In 2002, a concept study was started in Germany for an icebreaker with drilling capacity, the *Aurora Borealis*. The final design and budget estimate, in 2008, led the German Science Council to revise priorities, putting the construction of a successor of the icebreaker *Polarstern* upfront. In parallel, the extension of the drilling capacity of MARUM's robotic sea floor corer *MeBo* to a depth range of 200 m opens a vast range of opportunities in palaeoclimate studies. The evoked option of a couple of years of parallel operations of the existing and the new *Polarstern* in the northern and southern hemisphere might create a unique polar research momentum. In the UK, the BGS *Rockdrill* is another robotic seafloor drill rig, and a commercial ice-strengthened drill ship, the *Stena DrillMax Ice*, offers charter opportunities for science. In the years to come, Europe has quite a few assets in addressing the challenges of palaeoclimate research, from pole to pole.

Peering into recent climate variability: seabed and ice coring

When the French research and Antarctic supply vessel *Marion-Dufresne* was launched in 1995, equipped with the unique 60 m long *Calypso* piston corer, she already allowed a vast number of objectives of the palaeoclimate community to be addressed, well coordinated within the IMAGES programme (PAGES, IGBP). IMAGES (International Marine Aspects of Past Global Changes) closely dovetails with the CLIVAR programme (Climate Variability and Predictability) of the World Climate Research Program (WCRP).

The full unraveling of the recent glacial history of our planet, however, results from the coordinated analysis of seabed cores *and* ice cores. The ESF network GRIP (Greenland Ice Coring Project), funded by 8 European partners and the EU, successfully cored over 3,000 m of ice on the Summit site, central Greenland (1989-1992), providing the detailed northern hemisphere record of Earth's climate over the past 250,000 years. It would be relayed in 1999-2003 by the North Greenland Ice Coring Project (NGRIP).

Building upon that experience, the ECOPS Grand Challenge project EPICA drilled at Dome Concordia in Antarctica, from 1996 to 2005, again with support of the EC and national contributions. When drilling was completed, about 5 m above the bedrock, some 3,270 m of ice cores revealed a full sequence of eight glacial cycles, spanning 740,000 years, a record substantially longer than VOSTOK (which extended back to 420,000 years ago). Air bubbles in the ice revealed that atmospheric carbon dioxide levels remained below 275 ppm over this entire interval. In May 2013, the monitoring station at Mauna Loa recorded that CO_2 in our atmosphere, fueled by man-made emissions, had passed the threshold concentration of 400 ppm.

Margin process studies in the MAST era and FP5

The ESF Polar North Atlantic Margins Network (PONAM) contributed to increasing our understanding of the Late Cenozoic history of the European Arctic bordering the Norwegian and Greenland Seas, both in marine and terrestrial environments. It is among the first collaborative programmes in Europe showing the flag of 'margins' research. The Grand Challenges on the Arctic Ocean and the Deep Sea Floor further were concretised in a range of integrated projects under MAST 2 (FP3). No fewer than eight projects rallied to the common objective of the study of exchange processes at the continent-ocean margin in the North Atlantic. Among them the very large integrated project OMEX (Ocean Margin Exchange), ENAM (European North Atlantic Margin: Sediment Pathways and Fluxes), SEEP (fluid seepage along the continental margin) and STEAM (Sediment Transport on European Atlantic Margins), of which some would continue in MAST 3 (ENAM II, OMEX II, FP4). This effort did not remain unnoticed across the Atlantic: the considerable momentum in European margin exchange process studies had achieved an integration that went beyond the level established in the United States, and they were challenging US scientific leadership in this topical area (Mooers et al. 1996).

The momentum indeed continued through MAST 3 and even increased in the subsequent Sustainable Marine Ecosystems Key Action of the 5th Framework Programme (FP5). In the latter, a number of clusters of funded research projects were formed, such as OMARC (Ocean Margin Deep-Water Research Consortium, 13 projects), ELOISE (European Land-Ocean Interaction Studies, as contribution to the LOICZ Core Project of IGBP, 25 projects under FP5, 54 projects since its inception), IMPACTS (Impacts of pollutants on the marine environment, 16 projects), EUROHAB (Harmful Algal Blooms, 8 projects under FP4-FP5), the Marine Biodiversity Cluster (12 projects) and the Operational Forecasting Cluster (23 projects). The projects under OMARC, of which many were rooted in the Grand Challenge of the Deep Sea Floor, are listed in Box 1.1. Some of them, such as COSTA, had started interacting with industry, in particular oil companies.

The goals set by ESF and the EC for the four ECOPS Grand Challenges, to achieve an impact on European ocean and polar life and environmental sciences for a period of 6-10 years, mobilising budgets of over 50 MECU each, had clearly been achieved. The OMARC cluster alone represents an EU contribution of 25 M€.

The rise of collaborative global studies in ecosystems, biodiversity and biogeochemistry

For many years, British oceanographic vessels had been staffed predominantly by British scientists, French vessels by French scientists, German vessels by German scientists, etc., unless some foreign colleague was invited to bring specific expertise.

Box 1.1. **5th Framework Programme, Sustainable Marine Ecosystems Key Action**

Cluster OMARC (Ocean Margin Deep-Water Research Consortium)
ACES – Atlantic Coral Ecosystem Study
ANAXIMANDER – Exploration and Evaluation of the Eastern Mediterranean Sea Gas Hydrates and the Associated Deep Biosphere
COSTA – Continental Slope Stability
DEEPBUG – Development and Assessment of new Techniques and Approaches for Detecting Sub-Seafloor Bacteria and their Interaction with Geosphere Processes
ECOMOUND – Environmental Controls on Mound Formation along the European Margin
EURODELTA – European Coordination on Mediterranean Prodeltas
EUROSTRATAFORM – European Margin Strata Formation
GEOMOUND – The Mound Factory – Internal Controls
HYDRATECH – Techniques for the Quantification of Methane Hydrate in European Continental Margins
METROL – Methane Fluxes in Ocean Margin Sediments: Microbiological and Geochemical
PROMESS – Profiles across Mediterranean Sedimentary Systems
STRATAGEM – Stratigraphic Development of the Glaciated European Margins

Today, scientific shipboard parties on European vessels represent as a rule a spectrum of nationalities. This little revolution in Europe can be once more pinpointed to the magic turn of the 1980s into the 1990s. Two initiatives contributed in concert: (a) the start of the Marine Science and Technology (MAST) programme, which requested transnational collaboration to get EC funding, and (b) an Antarctic cruise leg on R/V *Polarstern* offered by the Alfred-Wegener-Institute for Polar and Marine Research in collaboration with ESF, the latter providing the networking funds in the framework of the European Polarstern Study – EPOS.

The EPOS Weddell Sea Ecology Study 1988-89 for the first time invited in a competitive context science proposals from all over Europe: for many European young scientists having otherwise no access to ships, and certainly not to the Antarctic, a dream came true. EPOS could not have made a better promotion for the dawn of the MAST years, and considering the success, the operation was repeated with EPOS II in 1991 on the European Arctic shelf.

While the theme of biodiversity had been prepared as a potential Grand Challenge, eventually it was not promoted as such at the Bremen 1994 Conference. This would not prevent ecosystems and biodiversity moving *en force* onto the agenda of European ocean and polar sciences in subsequent years. In FP5, all relevant marine research would be put under the Sustainable Marine Ecosystems Key Action, and in FP6 under Sub-Priority Global Change and Ecosystems. As a matter of fact, under FP5 and FP6, life and environmental sciences in the marine and polar realm in general moved forward in integrated, multidisciplinary projects.

The world of ecosystems in the deep sea and on continental margins indeed became much more diverse than anyone could ever have anticipated. In the early 1990s, ODP had revealed a totally unexpected 'Deep Biosphere', a microbial world extending over 700 to 800 m below the seabed. Cold seeps in the Black Sea, mud volcanoes from the Nile delta to the Norwegian margin and seafloor brine lakes on the Mediterranean Ridge turned hotspots of microbial communities. Calving ice shelves uncovered unexpected ecosystems. Cold-water coral reefs, most of them known to fishermen for years, were re-discovered in the spotlights of remotely operated vehicles in depth ranges between 300 and 1,200 m, off Norway, Scotland and Ireland, in the Bay of Biscay and on many sites in the Mediterranean. Deep water canyons turned out to be important refuges, and conservation issues came high on political agendas: deep water marine protected areas came into being.

In the direct post-MAST times, under FP5, it was still the environment that was the unifying theme of many projects (slopes, sedimentary systems, canyons, seeps and gas hydrate systems, mounds, deltas, etc., cfr. Box 1.1). From the large integrated projects and networks of excellence of FP6 onwards, ecosystems and biodiversity took the driver's seat, with, in particular, the large Network of Excellence MARBEF (Marine Biodiversity and Ecosystem Functioning) and the suite of large-scale Integrated Projects HERMES (Hot Spot Ecosystems Research on the Margins of European Seas) in FP6 and HERMIONE (Hotspot Ecosystem Research and Man's Impact on European Seas) in FP7.

The evolution towards large-scale integrated projects and networks was not only strategic, it was also a pure management necessity for the European

Commission. The marine projects enumerated earlier in the clusters of the Sustainable Marine Ecosystems Key Action of FP5 come to a total of 126. Rather than clustering *a posteriori* individual research projects (some of them already sizable) as under FP5, the policy of FP6 was to forge *a priori* large Integrated Projects – like HERMES – and Networks of Excellence (e.g., MARBEF). Even doing so, the EC was confronted with a total of 479 marine related science and technology projects in FP6, representing some 3.3% of the total of 10,490 funded projects (FP6 budget: 17.9 B€). It is not unexpected that with the further budget rise of FP7 and Horizon 2020 to respective levels of 50.5 and close to 80 B€, the overall enlargement of project scale is here to stay. The last call of FP7 addressing ocean sciences, 'The Ocean of Tomorrow' (2010-2013) – announced as 'Joint Research Forces to Meet Challenges in Ocean Management' – came to support some 31 projects, many counting between 20 to 38 participating teams. In such development, attention may have to be paid to the impact of this enlargement of scale on opportunities for university research units to take a fair lead in projects and secure the valorisation of their intellectual property, a crucial element for the sustainable generation of Europe's brainpower.

The momentum achieved through Europe's framework programmes shaped increased opportunities for European teams to join international efforts or overseas initiatives. Many European teams contributed to the Census of Marine Life project (CoML), funded by the US Sloan Foundation for a term of 10 years. This would become an important stimulus for biodiversity research. The concept of CoML would find some continuity in Europe from 2013 onwards, for marine and continental life, in the ESFRI E-Science LifeWatch project: a European Infrastructure for Biodiversity and Ecosystems Research.

At the beginning of the 21st century, ecosystems research also penetrated more deeply into global ocean circulation and Climate Change studies, which formerly had been dominated by physical and chemical oceanographers. A Global Ocean Ecosystem Dynamics study (GLOBEC), conceived in 1990 and integrated as IGBP Core element in 1995, was implemented from 2000 to 2010. In 2005, it branched into the IGBP-SCOR programme IMBER (Integrated Marine Biogeochemistry and Ecosystem Research), which studies the sensitivity of marine biogeochemical cycles and ecosystems to global change. European teams would take an important role in these programmes, as in related programmes in the Southern Seas, which were stirred by the dynamics of the 4th International Polar Year (2007-08). ICED – Integrating Climate and Ecosystem Dynamics in the Southern Ocean – and EBA (Evolution and Biodiversity in the Antarctic), a SCAR scientific umbrella programme (Box 1.4), are representative examples.

A major support programme for the study of biogeochemical cycles and ecosystem exposure to global change is GEOTRACES, which since 2006 resumes the strategy of geochemical cross sections pioneered in particular in the early 1970s by Wally Broecker in the GEOSECS programme (Geochemical Ocean Sections Study). GEOTRACES is an international programme which aims to improve our understanding of biogeochemical cycles and large-scale distributions of trace elements and their isotopes in the marine environment. It groups 35 nations and has already published some spectacular biogeochemical 3D maps in *Nature*.

Peering into the near future: IPCC as the star of the *fin de siècle*

The World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in 1988 under the umbrella of the World Climate Research Program (WCRP) with the assigned role of assessing the scientific, technical and socioeconomic information relevant to understanding the risk of human-induced Climate Change. The IPCC does not directly support new research or monitor climate-related data, but the process of synthesis and assessment has often inspired scientific research which would lead to new findings (Le Treut and Somerville, coord., 2007).

The IPCC has three Working Groups and a Task Force. WG I assesses the scientific aspects of the climate system and Climate Change, while WG II and III respectively assess the vulnerability and adaptation of natural or socioeconomic systems to Climate Change, and the mitigation options for limiting greenhouse gas emissions. The Task Force is responsible for the IPCC National Greenhouse Inventories Program. Obviously, the actions of WG I are closest to ocean and polar life and environmental sciences, and they have introduced a new concept in these sciences: the assessment and description of uncertainty.

A main activity of the IPCC is to provide on a regular basis an assessment of the state of knowledge on climate change. Five assessment reports have been released – the first assessment report

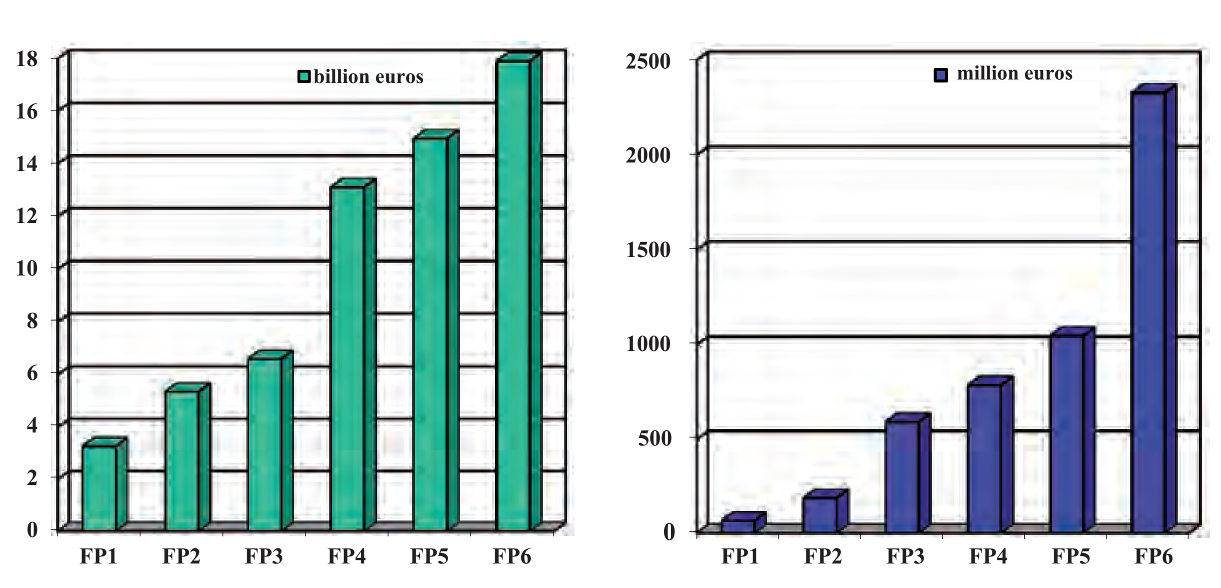

Figure 1.4. Evolution of the Framework Programme budgets and the EC budgets for training and education from FP1 to FP6 (source: European Commission).

(FAR) in 1990, the second one (SAR) in 1995, the third one (TAR) in 2001, the fourth one (AR4) in 2007 and the fifth one (AR5) in 2014. The WG I SAR, under Bert Bolin as IPCC Chair, provided a key input to the negotiations that led to the adoption in 1997 of the Kyoto Protocol.

Horizon 2020 would become the first EC Framework Programme to provide explicit support to IPCC, in the context of its first Work Programme 2014-2015.

Human Resources and Infrastructure for European Ocean and Polar Sciences

The pioneering EPOS Weddell Sea Ecosystem Study in 1988-89 exemplifies what young researchers need in Europe to move into ocean and polar research: (1) a fair opportunity of transnational access to a research vessel, (2) some mobility support for travelling to and from the vessels and the European research labs where the analytical work can be started, when not in the home institution, and (3) a research grant, either PhD or postdoctoral, to support them in the years of exploitation of the results. Such opportunities need to be made available year after year, as each year a new promotion of young graduates stands eager to sink their teeth into a legitimate share of the science cake, and as society needs a steady input of new brains, for innovation and development.

In the EPOS network, the ship was provided by the public research organisation AWI and the mobility support by the ESF. In the early years of European collaborative research, the sources for PhD grants were mainly the national research agencies. The postdoctoral system was still in its infancy. As the EC Framework Programmes developed, increasing opportunities were shaped within research projects, and not least within a mobility scheme which soon become well known under the label of Marie Curie fellowships. It is but recently that Maria Sklodowska's legitimate recognition of identity has been met by the EC.

The provision of networking funds in a flexible way would become a trademark of the European Science Foundation. Yet, in those same magic years of the end of the 1980s, the EC launched in 1987 the programme which qualifies to become its trademark: Erasmus. From the very first year onwards, BSc to MSc students moved around universities, marine institutions, ships and summer schools in Europe, with support of Erasmus grants.

As framework programmes geared up, so did the educational and training grants, both in the Marie Curie scheme and those built into the research grants. Some dedicated research and training networks were also created with EC support. An example in marine ecosystem research and margin studies was the FP5 network EURODOM (European Deep Ocean Margins). The budgets for education and training, however, did not faithfully follow the growth of the overall framework programmes (Figure 1.4), in particular in FP4 and FP5. The increase in budget for training and education was, however, very significant in FP6, in the years 2003 to 2007. The many young researchers who obtained a grant in that period would become available for science and society with the full benefit of that training some four to five years later, in the period 2008 to 2012.

The absolute star in the European individual research grant system is, however, the European Research Council (ERC). Officially launched in 2007 for a period of seven years, in 2013 it entered a second phase in Horizon 2020, as a major component of the 'Excellent Science' pillar.

Besides the vessels made available in Europe at the pace of EC research programmes by national agencies, one externally driven scheme would gain fame: the Training Through Research scheme (TTR, also known as 'Floating University', 1991-2010) under the leadership of Professor Mikhael Ivanov from Moscow State University, on board the large Russian research vessel *Professor Logachev*. This unique scheme, under the umbrella of IOC-UNESCO, functioned through bottom-up financing of European universities and research laboratories, coordinated by Royal-NIOZ in The Netherlands. For a few years, it also got support from an ESF networking grant. A total of 18 two- to three-month long cruises over a period of 19 years, each comprising several legs, would provide to over a thousand young scientists an unforgettable and rigorous training in marine acquisition techniques, from coring and dredging to sidescan sonar and reflection seismics. Many discoveries or follow-up studies of mud volcanoes, carbonate mounds and cold-water coral reefs, slope instabilities, gas hydrate fields and methane venting sites along the European continental margins can be credited to TTR. IOC-UNESCO provided the publication scheme of professional annual reports, which faithfully followed each large-scale post-cruise meeting and research conference.

Another scheme that deserves attention is the FP7 EUROFLEETS programme, 'Towards an Alliance of European Research Fleets'. It is a call-driven programme which provides transnational access to a wide range of European vessels and tools. The successful EUROFLEETS I programme (2009-2013) was followed by EUROFLEETS II (2013-2017).

The Cascais Initiative

Exactly 20 years after the joint declaration of Umberto Colombo and Paulo Fasella, on 10 February 2011, a panel of scientists who all have taken the lead in ESF Collaborative Research Programmes (EUROCORES) (Box 1.2) or in international programmes or commissions committed to ocean and polar life and environmental sciences convened in Cascais (Portugal) under the auspices of the European Science Foundation and the European Polar Board to reflect on long-term and widely multidisciplinary collaborative opportunities. The venue couldn't have been better chosen: a small but interesting museum close to the seashore vividly evokes the oceanographic research carried out between 1896 and 1907 by Dom Carlos de Bragança (King Carlos of Portugal) on board four dedicated yachts – *Amelia I* to *Amelia IV* (Saldanha 1980, Carpine-Lancre 2001).

The year 2011 was a crucial milestone for the conclusion of several EUROCORES and Research

Box 1.2. EUROCORES

The EUROCORES Programme was launched by ESF in 1999 to enhance the ESF's ability to leverage the collective expertise and resources of its 65 Member Organisations. A EUROCORES is a science programme that addresses a topic that is best tackled on a European multinational basis. The topic emerged from the scientific community but, as a first step, it needed to be ratified by the ESF Member Organisations (i.e., those having interest in the topic) through funding commitments. The next stage was the issuing of a common call followed by a thorough peer review of the proposals. The outcome of the reviewing formed the basis for Member Organisations to allocate funds to their own national research groups. In that sense the cost was meant to be generally neutral in overall terms. Partnership arrangements were meant to be important, and targeted in particular the European Commission (Banda 1999). This goal was reached in the 6th Framework Programme, when the EUROCORES Programme was granted 20 M€ from the EC ERA-NET Programme.

In addition to the EUROCORES grants, each EUROCORES Programme comprised a significant budget for networking and dissemination, which could be used under terms comparable to those of the successful ESF Research Networking Programmes (RNP). The force of the networking grants both under EUROCORES and the RNP scheme resided in their accessibility and flexibility, which offered to young scientists in particular opportunities to test and develop grand ideas – *their ideas* – in small, incremental steps.

Box 1.3. EUROCORES programmes and actions represented at the 2011 Cascais event

EuroDEEP *– Ecosystem Functioning & Biodiversity in the Deep Sea* – aims at the exploration and the identification of the different deep sea habitats, assessing both the abiotic and biotic processes that sustain and maintain deep sea communities in order to interpret variations of biodiversity within and between deep sea habitats and the interactions of the biota with the ecosystems in which they live. EuroDEEP funded projects are: BIOFUN, CHEMECO, DEECON, MIDDLE.

EuroDIVERSITY *– Challenges of Biodiversity Science* – aims to support the emergence of an integrated biodiversity science based on an understanding of fundamental ecological and social processes that drive biodiversity changes and their impacts on ecosystem functioning and society. EuroDIVERSITY funded projects are: METHECO, ASSEMBLE, COMIX, MiCROSYSTEMS, BIOPOOL, BEGIN, EcoTRADE, MOLARCH, BioCycle, AGRIPOPES.

EuroMARC *– Challenges of Marine Coring Research* – is a scientific programme to obtain key cores from the sub-sea floor that are crucial to progress in the earth and environmental sciences. Oceans indeed regulate climate, cover sites of fundamental geodynamic, geochemical and biological processes and preserve high-resolution records of the last 180 Ma of Earth's history.

EuroMARC funded projects are: CARBONATE, CHECREEF, MOCCHA, RETRO, AMOCINT, GLOW, H2DEEP.

TRACES *– Trans-Atlantic Coral Ecosystem Study* – is a scientific programme to investigate cold-water coral communities found along the continental shelf break and slope, and in association with canyons and seamounts in the North Atlantic Ocean. The success of TRACES relies on scientific cooperation between Canada, the European Union and the United States.

Networking Programmes initiated under the Life, Earth and Environmental Sciences domain of the European Science Foundation. In that framework, the development of a roadmap for long-term and widely multidisciplinary collaborative opportunities and synergies among the scientific communities associated to the EUROCORES Programmes EuroDIVERSITY, EuroMARC and EuroDEEP plus TRACES was considered a paramount priority for 2011. The goal was to stimulate discussion and (1) to identify the scientific frontiers and priorities linking the above mentioned communities, and (2) to explore potential connections to other research topics developed by already existing scientific clusters. These include clusters associated in international polar projects on climate evolution, biodiversity, life response to changes and life in the Polar regions. The objective was to devise the best strategy which might boost the implementation of new scientific collaborations in cutting-edge topics. A first session of the workshop was dedicated to an overview of the achievements of the EUROCORES Projects, while a second session covered the relevant polar projects (Boxes 1.3-1.4).

Boxes 1.3 and 1.4 frame the background of the scientists who convened in Cascais:

- On one side, a community focusing on palaeoclimate and palaeoceanography, which had largely shaped its cohesion around large ocean drilling ventures and/or ice coring (EuroMARC, ANDRILL)
- On the other, a vast community focusing on ecosystems, biodiversity and ecosystem services, largely in the deep sea and in polar seas (EuroDEEP, EuroDIVERSITY, TRACES, CAREX, CCAMLR, EBA, ICED, IMBER).

In all logic, the messages conveyed by the above communities to identify scientific frontiers and priorities will also reflect a dual structure:

- The palaeoclimate community will argue in Chapter 2 how rates of variation of climate at various temporal scales, documented in sediment archives and ice cores, may provide invaluable clues to key processes of climate dynamics, and lift a corner of the veil on the future development of our planet's climate
- The community focusing on ecosystems, biodiversity and ecosystem services discusses in Chapter 3 how the steady advance in our understanding of the functioning of marine systems and ecosystems, from tropical seas to high latitudes and from open ocean to confined seas, may help to assess the impact of climate change on the delivery of vital marine ecosystem services.

Box 1.4. European and international networks, polar commissions and programmes represented at the 2011 Cascais event

ANDRILL – *Antarctic Geological Drilling* – is a multinational collaboration to recover stratigraphic records from the Antarctic margin using Cape Roberts Project technology. The chief objective is to drill back in time to recover a history of palaeoenvironmental changes that will guide our understanding of how fast, how large and how frequent were glacial and interglacial changes in the Antarctic region.
CAREX – *Life in Extreme Environments* – is a network that addresses four themes: (1) Contributions of life in extreme environments as biogeochemical cycles and responses to environmental change, (2) Stressful environments – responses, adaptation and evolution, (3) Biodiversity, bioenergetics and interactions in extreme environments, (4) Life and habitability.
CCAMLR – *The Commission for the Conservation of Antarctic Marine Living Resources* – was established by international convention in 1982 with the objective of conserving Antarctic marine life. This was in response to increasing commercial interests in Antarctic krill resources, a keystone component of the Antarctic ecosystem.
EBA – *Evolution and Biodiversity in the Antarctic* – is a SCAR scientific umbrella programme covering with five work packages the entire Antarctic marine, terrestrial and aquatic biomes: (1) Evolutionary history of Antarctic organisms, (2) Evolutionary adaptation to the Antarctic environment, (3) Patterns of gene flows and consequences for population dynamics (isolation as a driving force), (4) Patterns and diversity of organisms, ecosystems and habitats in the Antarctic, and controlling processes, and (5) Impact of past, current and predicted future environmental change on biodiversity and ecosystem function.
EPB – *European Polar Board* – is a European strategic science policy organisation for polar affairs. The EPB is concerned with major strategic priorities in the Arctic and Antarctic, the launching of joint research programmes, the coordination of polar research infrastructures and policy issues in the context.
ICED – *Integrating Climate and Ecosystem Dynamics in the Southern Ocean* – addresses circumpolar ecosystem operation in the context of large-scale climate processes, local-scale ocean physics, biogeochemistry, food web dynamics and harvesting. It was developed with the approval of the IMBER and GLOBEC programmes.
IMBER – *Integrated Marine Biogeochemistry and Ecosystem Research* – was initiated by the IGBP/SCOR Ocean Futures Planning Committee in 2001, with the aim of investigating the sensitivity of marine biogeochemical cycles to global change, on time scales ranging from years to decades.

Opportunities for these communities to boost the implementation of new scientific collaborations within the framework of Horizon 2020 are discussed in the heart of Chapter 4.

Chapter 4 also provides a summary highlighting the principal conclusions and recommendations of the major scientific clusters and international organisations addressing climate change, life and environmental issues.

Companion reading

Hempel, G. (Ed.) (1996) *The Ocean and the Poles. Grand Challenges for European Cooperation.* Gustav Fisher Verlag, Jena, 381 pp.

Hay, W.W. (2013) *Experimenting on a Small Planet. A Scholarly Entertainment.* Springer, 983 pp.

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Chapter 2

Dynamics of the Ocean and Polar Environment on a Warming Planet

Jean-Pierre Henriet – Laura De Santis

Seafloor sediments form a faithful archive of the Earth's climate and of its variability, both cyclic and episodic. As such, they hold the key to the future of our planet's environment. In the following five essays, scientists of the Earth and the Ocean discuss a topic of their choice about the temporal evolution and spatial variability of the Earth's fluid envelopes, and argue what we should aim for.

While navigating in geological time studying temporal evolution and variability, we invariably shall refer to date and duration. In quantifying these, there is no unanimity. We shall follow the convention formulated by Aubry et al. (2009): geohistorical date, in years before present, is expressed in 'annus', symbol 'a', with the multiples 'ka' and 'Ma' meaning thousands and millions of years ago, and geohistorical duration being expressed in 'year', symbol 'yr', with multiples 'kyr' and 'Myr'.

One repository of information on past climates is the mass of tiny organisms of the sea – mostly foraminifera – that during a short lifetime captured in their shell subtle indicators of past environments, to subsequently accumulate and preserve this valuable message in seafloor sediments. An independent source of information was provided by samples of past atmospheres, trapped as microscopic air bubbles in continental ice sheets. How sediments help us to understand the climate system in the past, the present and the future is also summarised in *The Deep Sea and Sub-Seafloor Frontier* (Kopf et al. 2012, p. 15).

These indicators provide indirect evidence, they are 'proxies' for climate, and their diagnostic value depends on our insight into present-day analogues, our progress in modelling processes and responses, and our capacity to assess and cope with uncertainty. Such indicators document not only the astronomically paced cycles of warm and cold climates and major trends and events in climate change, but they also provide the clues for understanding our climate system's capacity to undergo abrupt changes in its mode of operation. The fundamental physical principles ruling climate dynamics are described in quite a few text books, such as William F. Ruddiman's *Earth's Climate – Past and Future* (2008), or the very recent and comprehensive textbook of Farmer and Cook (2013).

A first set of three essays in this section deals with the temporal variability of our planet's climate, zooming in from the broad picture of the past 65 million years to the latest interglacial stages, and next the most recent tens of thousands of years. Following Stephen Jay Gould's (1987) metaphor, we might say that the long-term cooling trend described by **Fabio Florindo and Stephen Pekar**, occasionally interrupted by ephemeral hyperthermal events, evokes "Time's arrow". The interglacial stages discussed by **Dick Kroon** in his quest for possible analogies with the present warm stage inherently belong to Gould's "Time's cycle". As to the abrupt changes described in the past tens of thousands of years by **Dierk Hebbeln**, they argue for the fact that the Earth's coupled ocean-atmosphere system has more than one stable mode of operation, as entertainingly narrated by Wally Broecker in his science thriller *The Great Ocean Conveyer* (2010): a thriller which we only could elucidate by unraveling the dynamics of deep ocean circulation.

The second set of two essays addresses spatially differentiated expressions of climate dynamics, as experienced in particular on Antarctic margins and in European confined seas. **Laura De Santis** discusses how the stability of Antarctic ice shelves is affected by warming water and rising sea level. The problem is that predictive models are simply not constrained by enough observations. Direct records are crucially needed to understand if the largest ice sheet of the planet ever collapsed in past times, at which rate, if coupled with ocean warming, with CO_2 increase, with ocean acidification, and finally how it contributed to ocean circulation changes and to a global sea level rise.

Gert J. De Lange draws our attention to the fact that some of the ocean sub-basins, ranking among the most vulnerable on Earth, are within the European realm: the Baltic, Mediterranean and Black Sea. All of them have suffered or still suffer from anoxic deep-water conditions, to various degrees. For the reader whose curiosity about the regional impact of climate change on Europe's ocean margins has been raised by Gert J. De Lange's essay, there is logical follow-up reading: ESF Marine Board's Position Paper 9 *Impacts of Climate Change on the European Marine and Coastal Environment*. For all regional seas surrounding Europe, this report presents a lucid account of signals of change and of projections of climate change, as well as of current research and monitoring programmes and projects (Philippart et al. 2007). As to the specific science challenges in polar seas and the Arctic in particular, they are thoroughly covered, for instance, in the classic Arctic Climate Impact Assessment (ACIA – Hassol 2004), and recently also in the EC-sponsored ERICON Science Perspective 2015-2030 (Willmott et al. 2013): a great science text, regardless of whether the *Aurora Borealis* drillship it meant to justify might, or might not, sail off the drawing board. The ERICON Science Perspective 2015-2030 has been adopted by the new EU/I3 initiative ARICE 'Arctic Research Icebreaker Consortium for Europe: A strategy for meeting the needs for marine research in the Arctic'.

Companion reading

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Chapter 2

Temporal Variability at Different Scales

Long-term climatic changes

Fabio Florindo – Stephen Pekar

According to the latest Intergovernmental Panel on Climate Change (IPCC 2013) report, the worst-case scenario projections (i.e., continued greenhouse gas emissions at or above current rates) will result by 2300 in global annual mean temperatures likely to exceed those that have been experienced on Earth in the last ca 40 million years, a time when ephemeral Antarctic ice sheets first developed. In light of increasing concerns over future climate change, a growing need exists to understand the dynamics and mechanisms of Earth's climate during specific periods of the geological past, when conditions of greater global warmth are known to have existed.

This is especially pertinent as climate models have in some cases underestimated current changes (e.g., in the Arctic region). Fortunately, the geologic record provides examples of how the climate system responded under elevated CO_2 levels, which can provide us with a glimpse of how our climate will respond to increasing levels of anthropogenic CO_2 in the atmosphere.

Over the past 65 million years, Earth's climate has undergone a significant and complex evolution, which was marked by reorganisation of global ocean circulation patterns and large temperature changes both in the sea and on land. This evolution

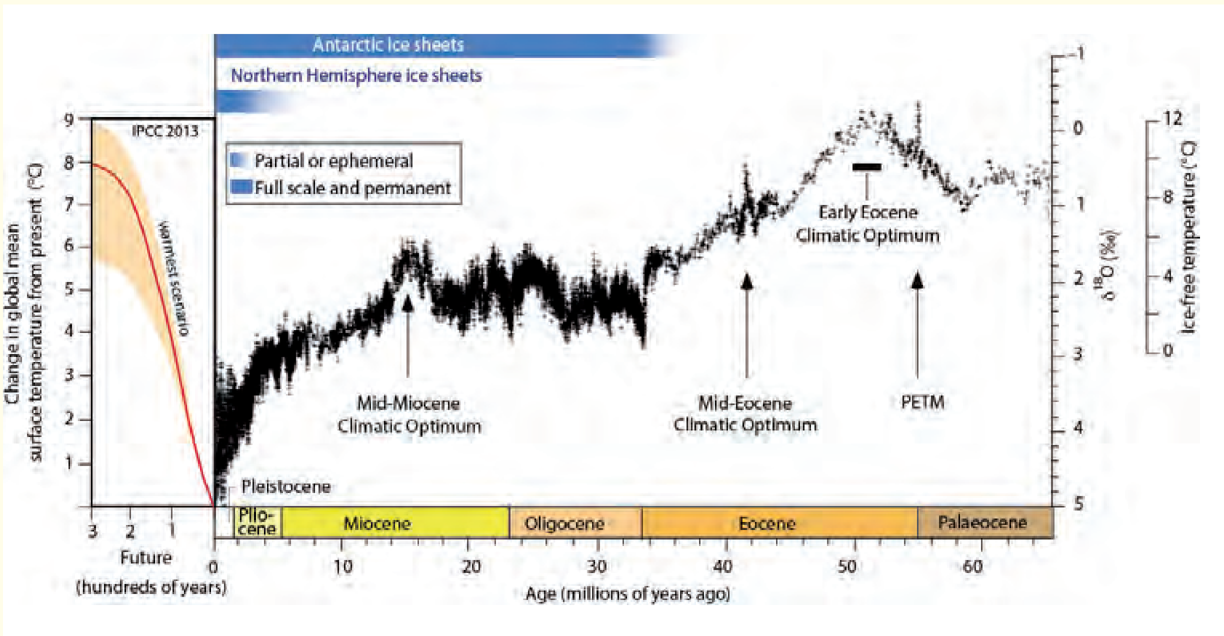

Figure 2.1. Global climate over the past 65 million years. The data are stacked from deep-sea oxygen isotope records based on data compiled from DSDP and ODP sites. The temperature scale on the right axis was computed on the assumption of an ice free ocean and therefore applies only to the time preceding the onset of large-scale glaciation on Antarctica (modified from Zachos et al. 2008). On the left, global annual mean surface temperature projections for the future show the increase in temperature under an "unrestricted" scenario (IPCC RCP8.5 unrestricted scenario), with continuing greenhouse gas emission beyond 2100 (modified from Barrett 2003).

includes gradual trends of warming and cooling driven by tectonic processes on time scales of 10^6 to 10^7 years, and abrupt shifts and extreme climate transients ('hyperthermals') like the Palaeocene-Eocene Thermal Maximum (about 56 million years ago) with durations of 10^3 to 10^5 years. Greenhouse gases (GHG) are considered a major causal factor for both long- and short-term changes. Quantifying how GHG affected these changes in the past is a major focus for scientists today because it may help to predict the consequences of unabated GHG emission in the future.

Background

Our knowledge of Cenozoic climate has been established primarily from studies of marine sediment archives from which we have unequivocal evidence that the climate over the last 100 million years has been characterised by exceptional warmth followed by an overall global cooling trend culminating in polar ice growth. Superimposed upon this long-term trend are numerous fluctuations in global cooling and warming (e.g., Zachos et al., 2001).

On a long-term view, a decrease in $\delta^{18}O$ of more than 1‰ is interpreted as an interval of global warmth occurred from the mid-Palaeocene to early Eocene (58-51 Ma), peaking with the Early Eocene Climatic Optimum (EECO) from 53 to 51 Ma. During EECO the partial pressure of CO_2 (pCO_2) is estimated at over 1,500 ppm, concomitant with global temperatures reaching a long-term maximum. Following this interval, global temperatures gradually decreased during the middle and late Eocene (ca 49 to 34 Ma), culiminating in the development of 'icehouse' climates with significant polar glaciation by the earliest Oligocene (ca 34 Ma). A transient warming event occurred between ca 22 and 16 Ma, with peak warmth reached during the Mid-Miocene Climate Optimum (MMCO) from about 17.0 to 14.45 Ma. This interval represents the warmest episode of the entire Neogene, and occurred when atmospheric pCO_2 concentrations were above 450 parts per million by volume (ppmv) (e.g., You et al. 2009). This warm phase was followed by a major climatic cooling over the next 6 Myr. Global cooling led to expansion of the East Antarctic Ice Sheet (EAIS) at 13.9 Ma, which was associated with a global sea level fall, a decrease of 6-7°C in Southern Ocean sea surface temperatures (SSTs) and deep-ocean cooling of 2-3°C. The deep-sea $\delta^{18}O$ records register this progressive cooling through the late Miocene, followed by a warming interval from 6 to 3.2 Ma, and then a further cooling leading to the onset of Northern Hemisphere Glaciation.

Superimposed on the long-term change from a hothouse to icehouse world, the deep-ocean records document brief ephemeral events (< 10^5 years) that are often accompanied by major perturbations in the global carbon cycle. Among these, the most prominent hyperthermal was the Late Palaeocene Thermal Maximum (LPTM), which occurred at 56 Ma near the Palaeocene/Eocene boundary. This event was characterised by a 5° to 6°C rise in deep-sea temperature in less than 10,000 years (>1.0‰ negative $\delta^{18}O$ excursion) and an abrupt negative global carbon isotope excursion of some 3.0‰, which has been interpreted as a rise in greenhouse gas concentrations, most likely from the dissociation and subsequent oxidation of marine clathrates. Another transient warming episode is the Middle Eocene Climatic Optimum (MECO) that occurred at 40 Ma and lasted less than 500 ka (Bohaty et al. 2009). Assuming minimal glaciation in the late middle Eocene, ca 4°-6°C total warming of both surface and deep waters is estimated during the MECO. The coincidence of marine warming and CCD shoaling during this event indicates a link to changes in atmospheric CO_2.

Present Understanding

Over the past 50 years, geologists have revolutionised how we understand our world, from the concept of plate tectonics to how astronomical cycles have paced our climate system, first recognised in Pleistocene records and now seen in time intervals throughout the geologic timescale. Today, geologists are attempting to address new questions that have perhaps even more relevance to societal concerns, namely how climate is changing from increases in greenhouse gases and environmental degradation. In the case of today, both result from anthropogenic causes; however, elevated greenhouse gases were the norm in the geologic past, providing scientists with examples of what our world could experience as CO_2 steadily increases in this century.

Given the current interest in the effects of CO_2 on climate, it may be surprising to learn that a great deal of uncertainty exists about the extent of the ice sheets and extent of the warmth during times when CO_2 was as high as is predicted for this century. Fortunately, a number of international programmes exist today, such as the Integrated Ocean Drilling Program (IODP, soon to be the International Ocean Discovery Program), International Continental Drilling Program (ICDP) and ANDRILL (Antarctic Geological Drilling) Program, that have the capability to obtain sedimentary archives that can provide new insights into how our climate has evolved during times of elevated atmospheric CO_2 level in the atmosphere.

Future Perspectives

In order to better understand Earth's response to rapid climate changes, and how different parts of Earth's climate system interact to amplify or diminish the effects of increasing global temperatures, scientists must investigate environmental information from deep-ocean sediments that were deposited millions of years ago when atmospheric CO_2 levels and global temperatures were much higher than today. However, missing data sets from critical areas of the world still hinder scientists from reconstructing the global climate picture. With such a paucity of information, it is critical to continue to collect and analyse environmental information from both deep-ocean sediments (e.g., using the riserless drillship *JOIDES Resolution*) and from the polar margin (e.g., using the ANDRILL deep drilling system from floating ice and using the shallow drilling tools, like MeBo, deployed on the sea floor, from ice breaking vessels) that were deposited millions to tens of millions of years ago when atmospheric CO_2 levels and global temperatures were much higher than today.

The take-home message

The geologic record provides a backdrop from which to understand relationships between climate changes and carbon cycling today. It has shown that concentrations of greenhouse gases and global temperatures have been higher in the past, providing examples of how Earth operated under elevated GHG. Therefore, it is only by obtaining and then exploiting these geological archives that we can assess the environmental changes that we are seeing today and are projected for our future. The various ocean, land and ice-based drilling programmes will provide the requisite data for assessing and meeting the challenges of the recent and future changes in Earth's various systems that are under threat from anthropological influences.

Companion reading

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Chapter 2

Super warm interglacials in the Pleistocene record

Dick Kroon

Statement

In the context of climate warming, satellite observations indicate that Arctic sea ice cover has seriously reduced in recent years. The ice has become so thin that it would inevitably disappear. It is alarming indeed that the Arctic sea ice cover hit a record low in 2012. The implications are serious: the increased area of open waters lowers the average albedo (reflectivity) of the planet, further accelerating global warming. Warmer seas could lead to more melting of Greenland's ice cap which could contribute to rising sea levels and could change the salinity of the sea, followed by changes in ocean surface and deep currents that help govern our climate elsewhere.

Present Understanding

This ongoing warming in the Arctic is unique for the past century, but has it happened before? To answer this question high resolution climate data on longer time scales are needed. High resolution sediment records, which can be recovered through ice, lake and ocean drilling, provide insight into natural climatic and oceanographic variability at decadal to millennial time scales. Several interglacials, during which the Earth was significantly warmer than during pre-industrial times, occurred in the last 1.2 million years (Figure 2.2). Studying these may contribute to the understanding of future climate warming of the planet, and may also contribute to the understanding of processes involved in returning to cold glacials. More specifically, results from proxy records combined with model simulations may not only shed light on processes involved in climate warming but most importantly also on regional effects of climate warming.

The predicted significantly warmer high latitudes in the near future justify climatic evaluations of older warm interglacials for comparison. Continuous ice core records from Antarctica and marine oxygen isotope records provide clear evidence of the persistence of glacial-interglacial cycles, and indicate that Marine Isotope Stages (MIS) 5 (85-130 ka), 11 (424-374 ka) and 31 (centered at 1.07 Ma, at the cusp of the Mid-Pleistocene Transition that is the interval of change from the 41 kyr obliquity-paced climate cycles to the 100 kyr cycles of the late Pleistocene) can be identified as super-interglacials, because temperatures rose generally higher in these periods than during the Holocene, reminiscent of our future climate (Figure 2.2).

The MIS 5e (Eemian) is the next oldest interglacial to the Holocene, which may serve well as a future analogue. Palaeorecords indicate a higher sea level, a smaller Greenland ice sheet, higher temperatures in the North Atlantic and adjacent continents. It is often quoted that generally warmer temperatures prevailed during MIS 5e because of the different orbital configurations than in the early Holocene.

But the general warming of sea surface and land temperatures may have led to increased melting of the surrounding large ice sheets and thus cooling may have occurred regionally. Although some progress has been made on documenting the magnitude of the sea level rise, knowledge of the waning of the Greenland ice sheet, and increase in sea surface temperatures in some areas, it is of the utmost importance to learn about feedbacks of substantial melt water runoff, diminished sea-ice formation, and response of surface ocean and deep water cur-

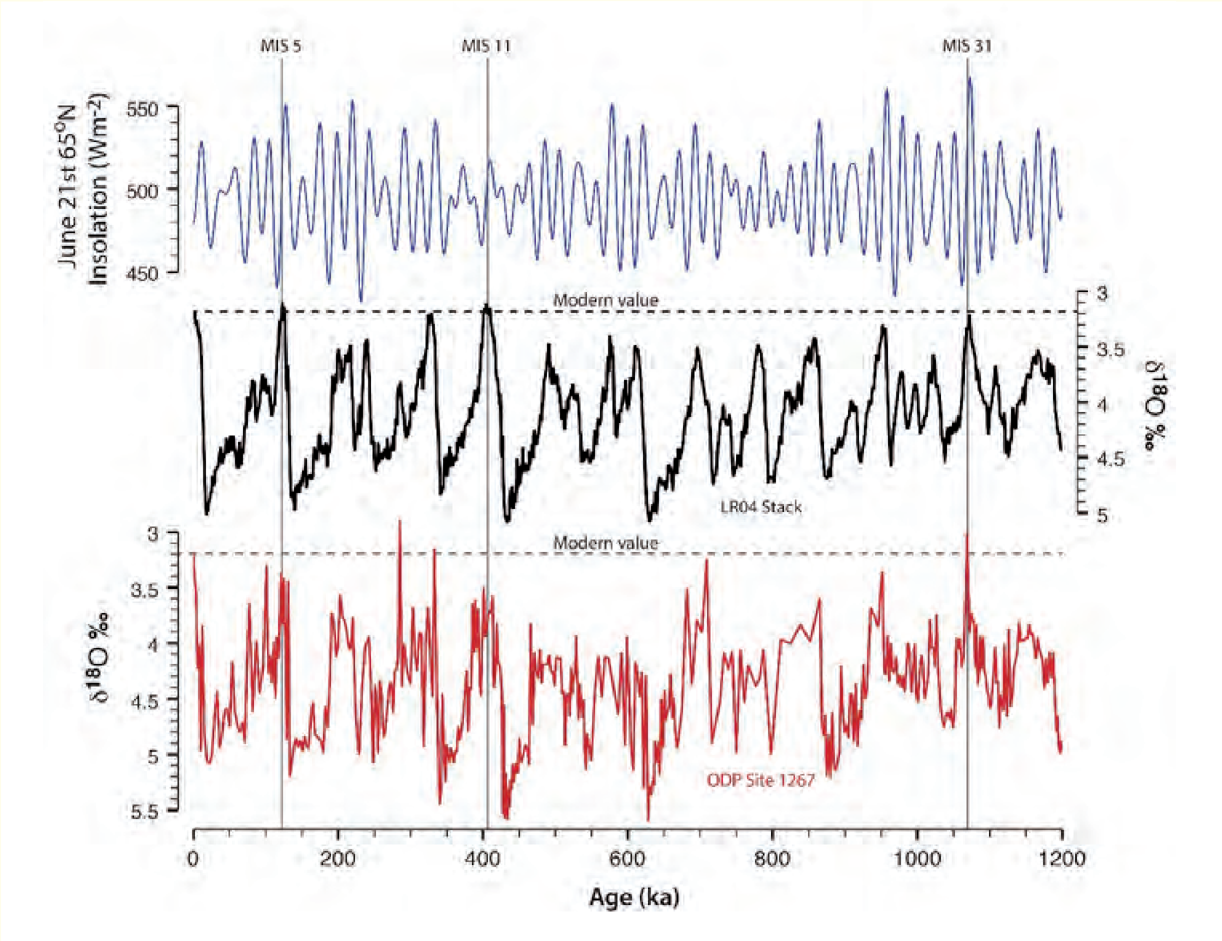

Figure 2.2. The marvelous stage 31 really stands out as a super-interglacial (particularly in site 1267). Stages 5 and 11 might look rather disappointing, but one super-interglacial isn't the other. Further, the insolation record shows that insolation driving stage 1 (and our future) is similar to stage 11. The site 1267 data come from the thesis of Dave Bell, University of Edinburgh.

rents during MIS 5, particularly now the sediment records retrieved from the sea bed have an appropriate time resolution, and age dating has improved, that rates of change in physical parameters can be quantified.

Rapid melting, commonly referred to as 'collapse' in the literature of the West Antarctic Ice Sheet (WAIS), would lead to a sea level rise of more than a metre in a century. Such 'collapses' have been suggested for the super-interglacials such as MIS 5 and MIS 11, but also for MIS 31. These 'collapses' were based on observations from palaeorecords of sea level such as deep sea $\delta^{18}O$ records. Attempts have been made to model variability in the volume of the WAIS in response to the glacial-interglacial cycles (e.g., Pollard and De Conto 2009). The simulated output predicted major 'collapse' and ice retreat during several interglacials in the last 1.2 million years or so, specifically when $\delta^{18}O$ minima coincide with strong austral summer insolation. The simulated 'collapse' at MIS 31 corresponds well with MIS 31, both in terms of timing and magnitude, but the simulated more recent 'collapses' do not coincide with the MIS 5 and MIS 11. This is surprising and may be an oversimplification of the modelling and/or there is a lack of palaeorecords. Obviously, it is of the utmost importance to obtain the best palaeorecords to verify modelling output to predict the future of ice retreat in such a sensitive place as West Antarctica.

Future Perspectives

The MIS 11 may serve as possibly the best analogue to our future climate because the orbital insolation pattern was similar to that of the Holocene. It is still under debate whether temperatures were warmer than in the Holocene and whether the sea level stood higher than today. MIS 11 may serve as a template to understand why this warm period returned into a cold period. It is of particular interest to learn how the climate responded to the reduced insolation levels, and which feedbacks were involved in accelerating the deterioration of climate. After all, the question arises whether our future climate will eventually become equally cold, or are concentrations of greenhouse gases induced by humankind to prevent this? Modelling may help to give the answer to this question, particularly if modelling is combined with observations from the palaeorecords such as past sea surface temperatures, sea-ice, and other parameters.

Palaeorecords combined with model simulations are extremely important to investigate causes and effects of climate development during the super-interglacials, and may elucidate the effects of climate warming in the climate sensitive high latitudes. It is needless to say that this is pivotal for understanding global climate change in the future on time scales directly relevant for humankind but also on time scales at the frequencies of orbital configurations.

The take-home message

Sediment cores combined with model simulations can be used to investigate causes and effects of climate development during these super warm periods, and may shed light on the effects of climate warming in the North Atlantic and Arctic in future.

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Abrupt climate changes

Dierk Hebbeln

Statement

Until the late 1980s the dominant view of past climate change focused on the comparably slow changes associated with the waxing and waning of continental ice masses leading into ice ages, or glacials, and periods as warm as today, known as interglacials. These climate changes are forced over millennia or even tens of millennia by the so-called Milankovitch cycles describing variations in the Earth's orbit around the sun.

However, since then much faster climate changes have been identified as common elements of the Earth's climate system. This at that time somewhat surprising result was based on the analysis of high-resolution ice cores drilled on Greenland. With their annual layering these ice core records allowed for an unprecedented reconstruction of past climate variability and revealed large and abrupt temperature shifts over periods as short as a thousand years (Dansgaard et al. 1993). These abrupt temperature variations, now well-known as Dansgaard-Oeschger oscillations (Figure 2.3), have subsequently also been found in other palaeoclimate archives around the world as, e.g., in marine sediments from the various ocean basins or in speleothem (cave dropstone) records.

Present Understanding

Based on such observations, the term 'abrupt climate change' is usually associated with the climate system crossing some threshold, triggering a transition to a new climate state (NRC 2002). Most intriguing, however, was the observation that the actual change from one climate state to another occurred in decades rather than in millennia. For instance, some 11,700 years ago, the climate in the North Atlantic region turned into a milder and less stormy regime in less than 20 years, accompanied by a warming of 7°C in South Greenland that was completed in about 50 years (Dansgaard et al. 1989) similar to a rapid warming around 45,400 years ago, when within 40 years the South Greenland temperatures rose by 6°C (Alley 2000, Figure 2.3). And such rapid warmings of several degrees C within a few decades appear to be a common pattern within the Earth's climate system, at least through the last 50,000 years (Figure 2.3).

In contrast, the present interglacial period, the Holocene, comprising the last ca 11,000 years, is usually seen as comparably stable. And although drastic climate changes as mentioned above are not known, severe droughts and other regional climate events have shown similar tendencies of abrupt onset and great persistence (NRC 2002).

Most notable among these are the late Holocene cooling/drying events that occurred 5,200 years and 4,200 years ago and during the Little Ice Age (ca 1300–1870 A.D.). Partly, such abrupt shifts had dramatic consequences for human societies as, e.g., the collapse of the classic Mayan civilisation caused by drought and the failure of the Viking settlements in Greenland caused by cooling. If such a rapid and sustained drought as during the 4,200 year event were to occur today, with Earth's population rapidly approaching 7 billion, the impact would be very troubling (Rashid et al. 2011).

At first glance, climate changes on decadal time scales might not appear as abrupt. However, at present humankind is – for good reason – trying to keep human-induced global warming below 2°C on a century time scale. The possibility of experi-

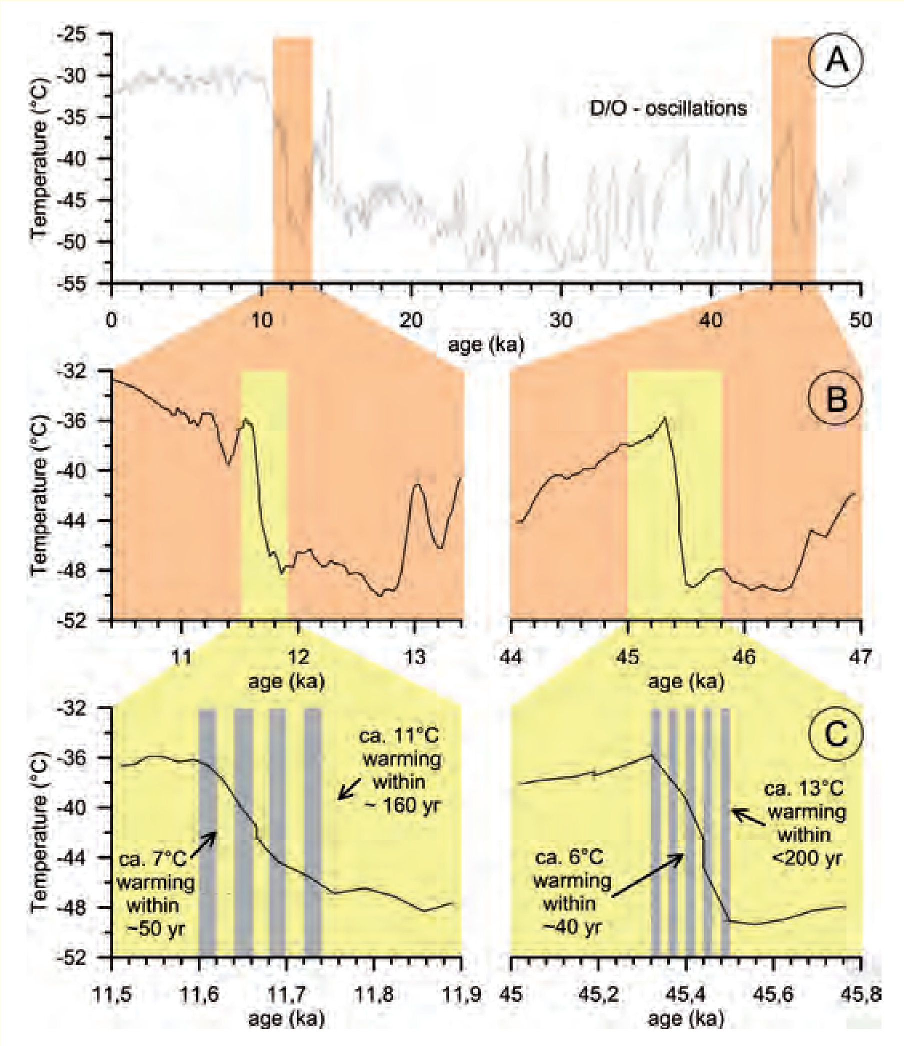

Figure 2.3. Temperature variability in South Greenland over the last 50,000 years reconstructed from stable oxygen isotope measurements on ice cores (Alley 2000). (A) Full record revealing highly variable conditions including the Dansgaard-Oeschger oscillations during the last glacial period and the rather stable conditions during the last ca 10,000 years, representing the Holocene. (B) Selected, distinct temperature changes shown on a millennial time scale. (C) Highlighting abrupt climate changes on decadal scales (grey bars represent 20 year intervals).

encing decadal shifts of >5°C would shed new light on the range of mitigation and adaptation strategies needed. Thus, from a societal point of view, an abrupt change is one that takes place so rapidly and unexpectedly that human or natural systems have difficulty adapting to it. Abrupt changes in climate are most likely to be significant, from a human perspective, if they persist over years or longer, are larger than typical climate variability, and affect sub-continental or larger regions (NRC 2002).

Future Perspectives

On geological time scales such abrupt climatic changes are likely to occur also in the future; however, with their forcing and dynamics still being only poorly understood, even state-of-the-art climate models can hardly provide any information on possible future events. Nevertheless, the most commonly invoked mechanisms related to abrupt climate change all see a very prominent role of the ocean as, e.g., (1) the interplay between freshwater/melt water forcing of the North Atlantic and the meridional overturning circulation, (2) changes in sea ice extent affecting the ocean-atmosphere heat exchange, and (3) sea surface temperature conditions in the tropics (Rashid et al. 2011).

Linked to crossing thresholds in the climate systems, the probability of abrupt climate changes might increase due to human forcing of climate change. Obviously, any such future rapid and dramatic changes would pose a significant threat to our societies and economies, highlighting the need for a much better understanding of the causes and effects of abrupt climate changes. This will require combined and ideally coordinated efforts to increase the temporal and spatial resolution of palaeoclimate reconstructions and of climate models focusing on past abrupt climate changes. Annually resolved ice cores from the Polar regions (and some (sub-)tropical high mountain ranges) and coral records from the tropical shallow seas probably provide the best palaeoarchives for these studies. However, their limited geographical coverage requires the use of additional palaeoarchives such as, e.g., marine sediments that can provide a wealth of information on various environmental parameters representing the state of the oceans. Thus, for the global database on past abrupt climate changes needed to inform the respective climate models, the collection and analyses of marine sedimentary records with decadal or higher temporal resolution should be high up on the research agenda for the coming years.

The take-home message

For the global database on past abrupt climate changes needed to inform the respective climate models, the collection and analyses of marine sedimentary and coral records with decadal or higher temporal resolution should be high up on the research agenda for the coming years.

Companion reading

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Chapter 2

Spatially Differentiated Responses

Sea level rise and the stability of ice sheets, from a geological perspective

Laura De Santis

Statement

Global sea level has risen about 120 m since ca 20 ka BP, the end of the Last Glacial Maximum (e.g., Peltier and Fairbanks 2006). Proxy records that are used to reconstruct the amount and rate of sea level rise include datings of fossil coral terraces and other calcareous shells of marine organisms from the sedimentary records. However, uncertainties in reconstructing the global sea level rise are affected by the precise dating of different records that are sometimes discrepant and by the estimate of local subsidence due to isostatic adjustment. The reconstructions became even more complicated and less confident with ancient records that preserve the imprint of glacial and interglacial sea level fluctuations, but the resolution of the dating methods and the distribution of geological record is low.

The Antarctic ice sheet is the largest on the planet and the least understood. Its overall mass balance is presently positive, even considering that large sectors of the West Antarctic Ice Sheet (WAIS) appear to be shrinking, as calculated by satellite images with large error bars (Shepherd et al. 2012). In some areas wide ice shelves have been disintegrating (e.g., the Larsen ice shelf) in the last 10 years and local observations and decadal measurements suggest that warming water is impinging the Antarctic continental shelf, e.g., in the Amundsen Sea (Rignot et al. 2008), and is melting the base of ice shelves (Jenkins et al. 2010, Jacobs et al. 2011), reducing their buttressing effect and causing upstream grounding ice to thin and grounding lines to retreat (Pritchard et al. 2012). This process results in large ice loss, via fast flowing streams.

Rignot et al. (2011) determined that ice sheet loss is accelerating three times faster than from mountain glaciers. The magnitude of the acceleration suggests that ice sheets will be the dominant contributors to sea level rise in forthcoming decades, and will likely exceed the IPCC projections (Meehl et al. 2007). The consequences of this ongoing process at global scale are still unknown. Models suggest that once the ice sheet buttressing by a large ice shelf is weakened, fast flowing ice streams can rapidly cause the dismantling of the most vulnerable sectors of the West Antarctic ice sheet where it is grounding below the sea level (Weertman 1974, Mercer 1978, Schoof 2007). These processes were observed on a smaller scale in the Antarctic Peninsula following the recent breakup of the Larsen B ice shelf (Scambos et al. 2004). Pulses of ice-sheet meltwater into the world ocean indeed occurred during the last deglaciation. The largest of them, the mwp-1a, quite well documented in several geological records around the world, caused 20 m of sea level rise in about 500 years (Peltier and Fairbanks 2006). However, the causes and consequences of such abrupt sea level rises and the relationship among the components of the ocean and cryosphere systems during such events are not clear. Clark et al. (2009) proved that a large component of mwp-1a originated from Antarctica. However, Mackintosh et al. (2011) found no evidence, at least in one site of the East Antarctic Ice Sheet, the Mac Robertson Shelf, of large contribution to mwp-1a. They also concluded that the initial stage of retreat, here, may have been forced by sea level rise, but that the majority of ice loss resulted from ocean warming at the onset of the Holocene epoch.

An important ongoing process that is observed to be occurring along the Antarctic margin as a consequence of ice melting under the action of warming ocean tongues is the freshening of the Southern

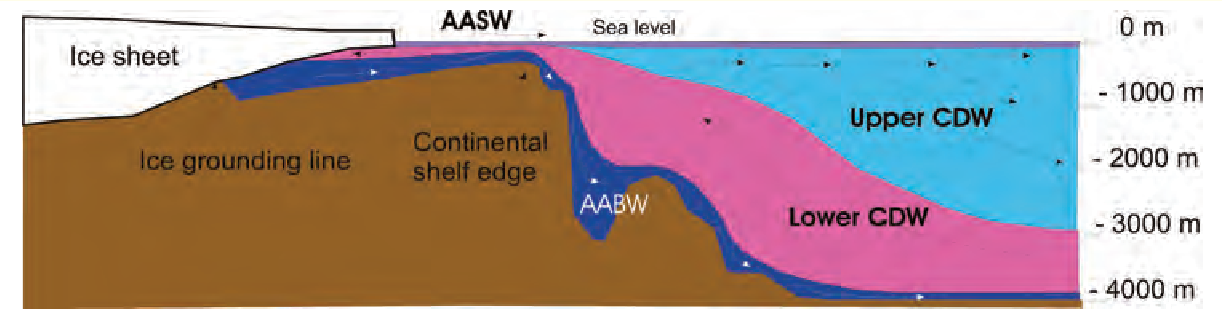

Figure 2.4. Cartoon illustrating the simplified water masses stratification across the areas of the Antarctic margin, where the warm ocean current reaches the ice front: 1) the cold dense bottom waters forming in the Antarctic continental shelf polynyas, spilling out the shelf edge, cascading downslope and flowing north (AABW), cooling the abysses of the global oceans; 2) the warmer Circum polar Deep Waters (CDW) coming from the lower latitudes, impinging the continental shelf, reaching and melting the ice shelves from below; 3) the Antarctic cold and fresh surface waters (AASW).

Ocean water (Jacobs and Giulivi 2010). This freshening is affecting the buoyancy, the stratification and the chemical composition of the different surface and bottom water masses (e.g., Rintoul 2007).

Also in this case the impact of this process at global scale is still unknown. Local observations reveal that such a change is modifying the biogeochemical cycles (e.g., Atkinson et al. 2004) and the formation of Antarctic Bottom Water (Purkey and Johnson 2010, 2012, 2013), the southern branch of the global thermohaline circulation. Like for the Northern Atlantic, if dense and cold water masses are not cascading from continental shelf to the deep Southern Ocean, the global conveyor belt might slow down and stop and this will cause dramatic climate changes at all latitudes.

Lack of understanding of how ice sheets and ocean dynamics might change in a warmer climate was identified in the IPCC Fourth Assessment as the largest uncertainty in predicting sea-level rise; in fact, so little is understood about the response of the Antarctic ice sheet to climate forcing, that it has simply been left out of many climate predictions.

Present Understanding

Advanced technology allows ongoing significant environmental changes occurring where the ice meets the ocean, on spots particularly sensitive to global climate warming, to be detected and measured. However, our knowledge about rates and amplitude of these changes, their link to orbital and to other factors driving climate and their impact on the rest of the planet is still poor. Future forecasts are still mainly based on theoretical models that urgently need direct observations and longer time series of data to provide realistic scenarios.

Past trends and events in Earth's climate history are known from the benthic oxygen isotope records collected by deep ocean drilling (Zachos et al. 2008). But their interpretation in terms of Antarctic conditions relies on more direct records, such as the time of occurrence of tills and the mapping of their maximum extension over the continental shelf, the occurrence of ice-rafted debris suggesting large ice mass wasting toward the ocean, the records of vegetation and landscape history.

Antarctic ice volume growth and shrinking, over several glacial and interglacial cycles, since the onset of the icehouse world (last 34 millions of years), resulted in building and shaping a wide continental margin with peculiar geology and morphology features. Multidisciplinary studies aimed at extracting from the geological record the information on the environmental conditions at the time of deposition of sediment in ice-proximal settings, when the temperature and CO_2 atmospheric content were higher than present, are a key to unravelling our future.

Grids of geophysical profiles tied to deep drilling data have been collected since the 1980s in Antarctic seas and allowed the Antarctic continental margin architecture, built and shaped by ice sheet advances and retreats, throughout the Cenozoic to be revealed.

Over-deepened (1,000 m) and landward dipping glacial troughs are typical products of erosion by ice streams over the continental shelf. Sediment stripped off from inland and the shelf is transported subglacially and delivered by the ice streams to form giant trough-mouth slope fans.

Palaeogeography change was reconstructed by mapping glacial stratigraphic sequences, since the onset of the icehouse world, in some regions of the Antarctic margin. However, due to the problems of recovering and dating glacial till, the Antarctic ice sheet history is still poor. Recent advances in drilling technology and in detecting past temperature biomarkers allowed high resolution palaeoclimate series to be recovered, tuned to Cenozoic orbital cycles (e.g., the ANDRILL project in the Ross Sea, Naish et al. 2009) and documenting, for the first time in detail, rates and modes of ice sheet dynamics during past super-interglacial changes. More of this kind of geophysical and geological records in other sectors of the Antarctic margin will be challenging to calculate the ice sheet hysteresis in its response to climate forcing in past warm and high CO_2 time intervals.

Sophisticated remote acoustic tools and advanced data processing are used to investigate grounding line processes and to measure water mass and sea bed properties processes. The new technology and the multidisciplinary approach allow us to estimate quantitatively the changes occurring today and those which occurred in the past at the cryosphere-hydrosphere boundary, and to distinguish the effect and role of ongoing environmental forcing. More of this kind of geological, geophysical and oceanographic records in different sectors of the Antarctic margin will allow the stability of the largest ice sheet on the planet to be monitored and shut-off signals in the global thermohaline southern source to be detected.

Future Perspectives

Geophysical and geological surveys are exploring the sub-glacial sediment and bedrock and the depositional processes occurring at the ice-grounding line of the main Antarctic ice streams. Geophysical exploration and deep and shallow drilling on the continental shelf, slope and rise are providing fur-

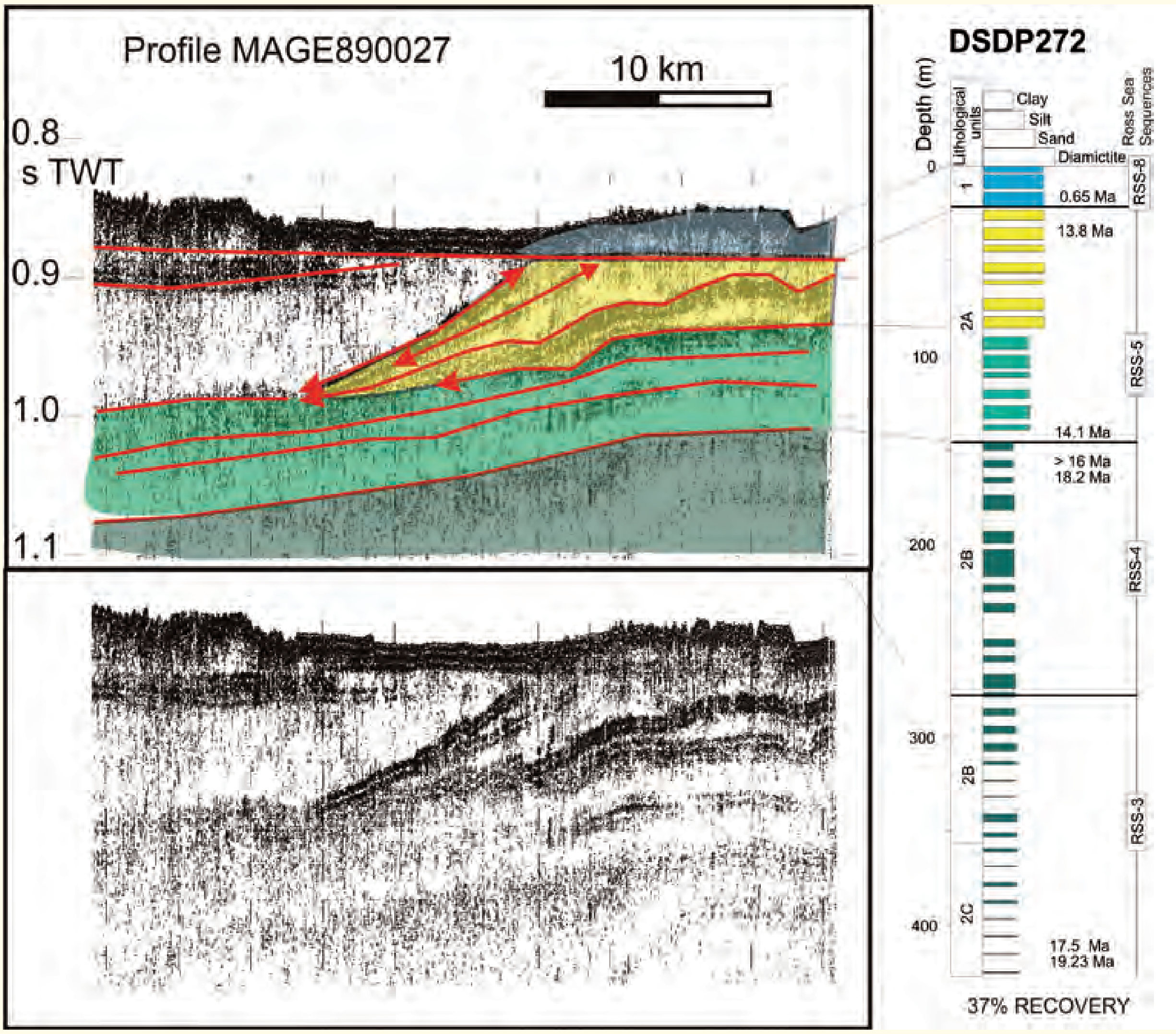

Figure 2.5. Figure showing an example of correlation between acoustic and sedimentary facies in the Ross Sea (West Antarctic margin). The seismic profile was collected by the Russian Marine Arctic Geological Expedition with Sparker in 1989. The drill site 272 was collected by the first Antarctic DSDP leg (Hayes et al. 1975). The yellow facies represents an ice proximal, foreset beds wedge. The green facies represents the sub-horizontal, ice distal marine deposits. The glacial prograding wedge, shown in the figure, documents ice expansion over the eastern Ross Sea continental shelf at the end of the Mid-Miocene Climate Optimum and coincides with the overall global cooling that led to a main expansion of the Antarctic ice sheet at 13.9 Ma, associated with a global sea level fall, a decrease of 6-7°C in the Southern Ocean sea surface and a deep-ocean cooling of 2-3°C. Figure is modified after De Santis et al. (1997).

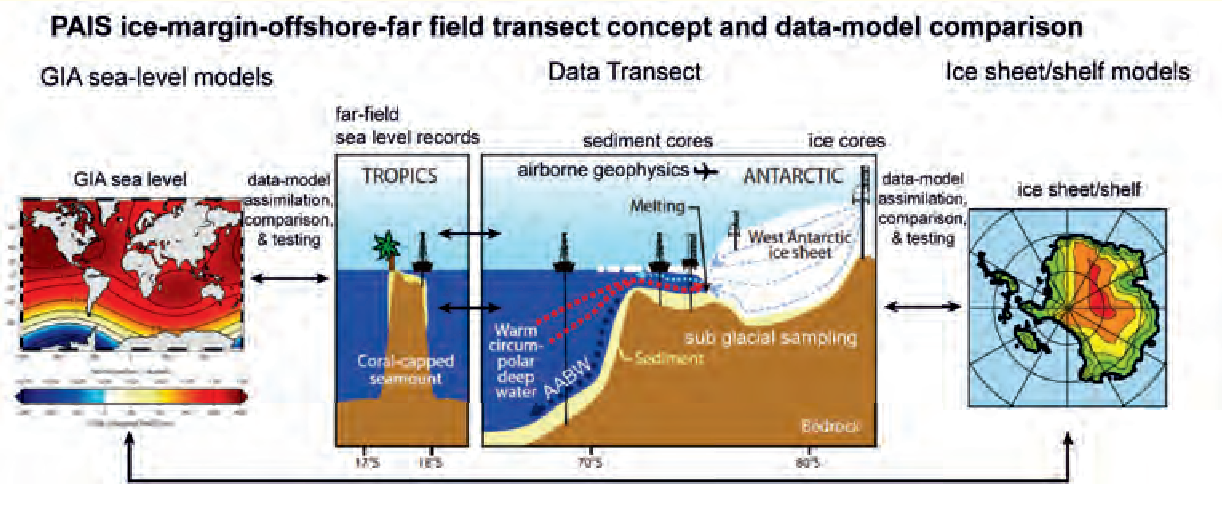

Figure 2.6. Figure showing the transect of drilling proposals from sub-ice to abyss or refer to the PAIS diagram. The central part of this figure is from the IODP Science Plan and illustrates the ice-to-abyss strategy for addressing these Challenges that has been adopted by the southern high latitude community. The flanking panels in the figure illustrate that to address the Challenges drilling results need to be integrated with ice sheet models and with Glacial Isostatic Adjusted gravitational models.

ther information on the Antarctic ice sheet, ocean gateways and palaeo-circulation evolution though time. New internationally coordinated multi-platform programmes linking depth and latitudinal transects from sub-ice to the continental shelf and the deep ocean are nucleating inside the SCAR/ACE (Antarctic Climate Evolution) and PAIS (Past Antarctic Ice Sheet dynamics) initiative.

Specific drainage basins will be targeted to account for different areas having experienced a different evolution. The transect approach will also constrain and test sea level changes across latitudes, based on 'Glacial isostatic Antarctic ice sheet–ocean–climate' models that require coeval near-field and far-field sea level histories. The SCAR/PAIS coordinated pan-Antarctic actions will address the objectives of the IODP Science Plan 2013-2023, Theme 1 (Climate and Ocean Change): *Challenge 1 – 'How does Earth's climate system respond to elevated levels of atmospheric* CO_2*?'* and *Challenge 2 – 'How do ice sheets and sea level respond to a warming climate?'*.

Multidisciplinary (including physics, biogeochemistry, sea ice, biology and surface meteorology) campaigns for monitoring the Southern Ocean are going to be implemented under the framework of the SCAR/SOOS (Southern Ocean Observing System) programme, extending from the Subtropical Front to the Antarctic continent and from the sea surface to the sea floor.

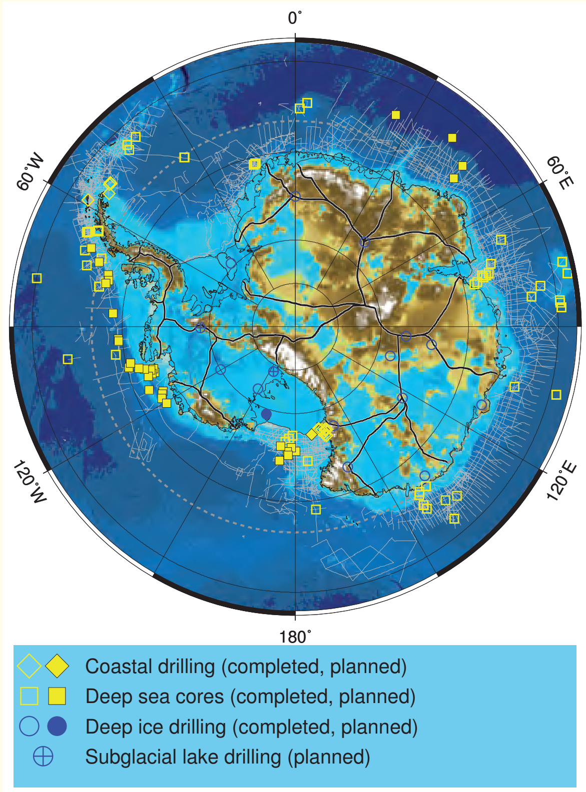

Figure 2.7. Figure from the SCAR/PAIS proposal showing the bed elevation below the Antarctic Ice sheet (modified from Lythe et al., 2001) showing the presently marine-based ice sheet sectors. They are particularly vulnerable to sea level rise and ocean water warming. Black lines delineate the main ice divides. White lines show the track of existing multichannel seismic profiles in the Antarctic continental margin (the source is the Antarctic Seismic Data Library System, SDLS http://sdls.ogs.trieste.it/). Bathymetry is from GEBCO. Completed/planned deep drill projects are also shown (see details in the Antarctic and Southern Ocean Future Drilling 2012 Workshop report at: http://www.scar-ace.org/work/Antarctic-drilling_workshop-2012_report%201.pdf). Graphic: Dan Zwartz

The take-home message

Main questions that will be addressed in the coming years are:
- How has ice behaved during past warm periods? Is there evidence of landforms scoured during outburst floods on the continental shelf of Antarctic subglacial basins, during past super-interglacial times of high temperature and high CO_2 content?
- Which is, and which was, the consequence on sea level rise and on thermohaline circulation (and the global climate) of such large freshwater discharges into the ocean?
- How are warm oceanic waters reaching the margin of grounded ice and how is the ice responding?

These questions cannot be answered using satellite data only, or by taking ships to the mid-latitudes. They are scientific questions that require the acquisition of long time-series of ocean observations and of high-resolution geological records, in positions both proximal and distal to the largest ice sheets. Offshore of the most vulnerable and highly dynamic areas, the thickest sediment depocenters document frequent ice advances and retreats. Here intense bottom currents flowing downslope, upslope and along the margin have re-shaped glacial sediment drifts. The investigation of depth- and latitudinal transects will help to understand if the ice sheet disintegrated in past times, at which rate, if coupled with ocean warming, with CO2 increase, with ocean acidification, and finally how it contributed to global sea level and ocean circulation changes.

Companion reading

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IODP Integrated Ocean Drilling Program SCIENCE PLAN 2013-2023 http://www.iodp.org/science-plan-for-2013-2023

SCAR/ACCE Antarctic Climate Change and Environment http://www.scar.org/publications/occasionals/acce.html

SCAR/SOOS Southern Ocean Observing System Initial Science and Implementation strategy http://www.scar.org/researchgroups/physicalscience/oceanography/

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Chapter 2

Past and potential future effects on the oxygenation level for vulnerable European basins: Baltic, Black and Mediterranean Sea

Gert J. De Lange

Statement

Some of the ocean sub-basins that are amongst the most vulnerable on Earth are within the European realm. All of them have suffered or still suffer from anoxic deepwater conditions. For the Black Sea, the seawater below some 70 m until its full water depth of about 2,243 m is permanently anoxic (i.e., totally devoid of oxygen) (e.g., Figure 2.8, Murray et al. 2005, 2013).

For the present Baltic Sea, nearly permanent anoxia occurs only in a few deep sites but seasonal deepwater anoxia is common (see example for 2010, Figures 2.9 and 2.10, and Conley et al. 2009).

The (eastern) Mediterranean is presently oxic but its deep water has been repetitively anoxic for extended periods of time, the most recent period was 6-10 kyr BP (Figure 2.11, De Lange et al. 2008). All three basins have a water circulation that is restricted due to the presence of a sill. Such restricted circulation not only reinforces the vulnerability and sensitivity to environmental changes, but it also makes the sedimentary archives of these basins a potential gold mine for high resolution palaeoclimate studies.

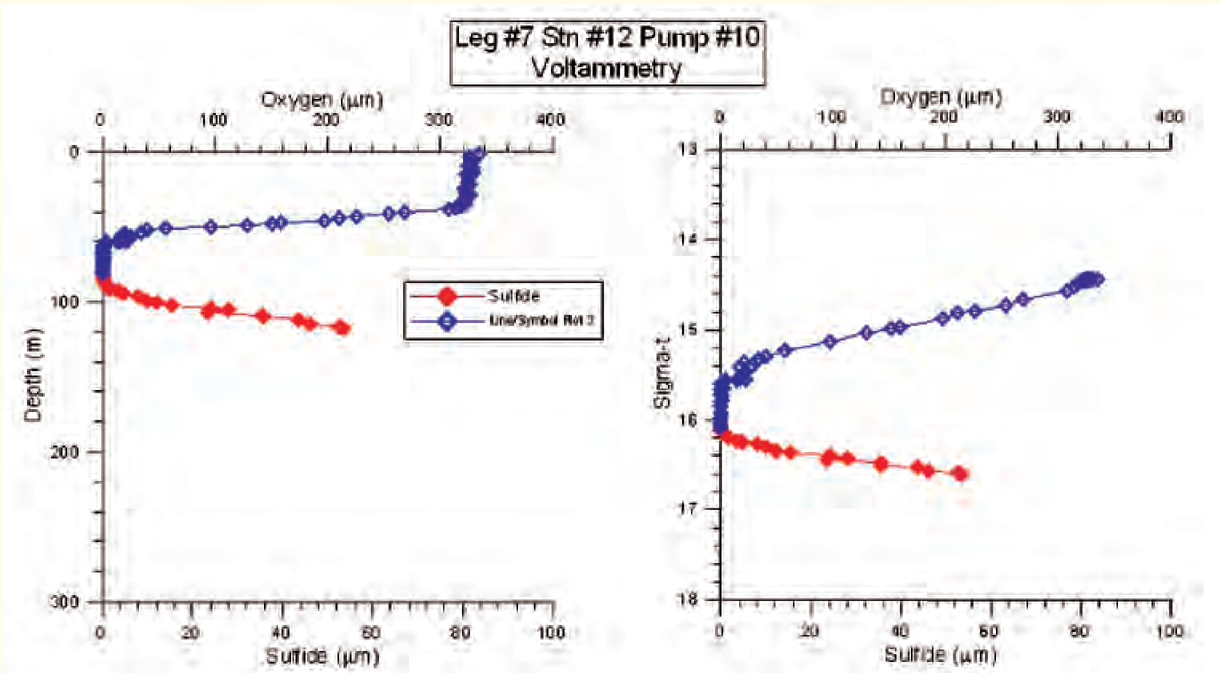

Figure 2.8. Oxygen and sulphide data from the centre of the western gyre in the Black Sea, R/V *Knorr* cruise 2003. Data courtesy of G. Luther (U. Delaware) and S. Konovalov (MHI, Sevastopol, Ukraine (Murray et al. 2005). Depth on the left and density on the right vertical axis. The first sulphide occurs at about 90 m.

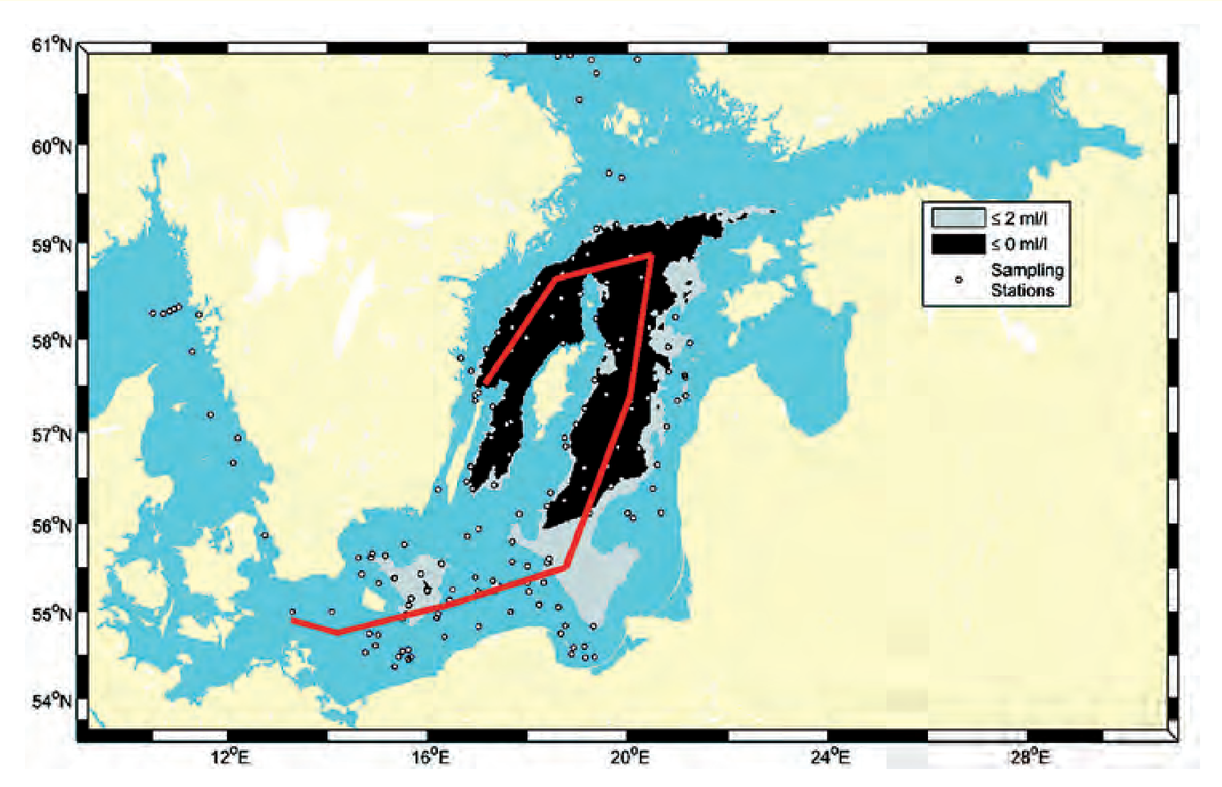

Figure 2.9. Extent of oxygen-free areas (black) and areas with oxygen deficiency (grey) in the Baltic during autumn 2010 (Hansson et al. 2010)

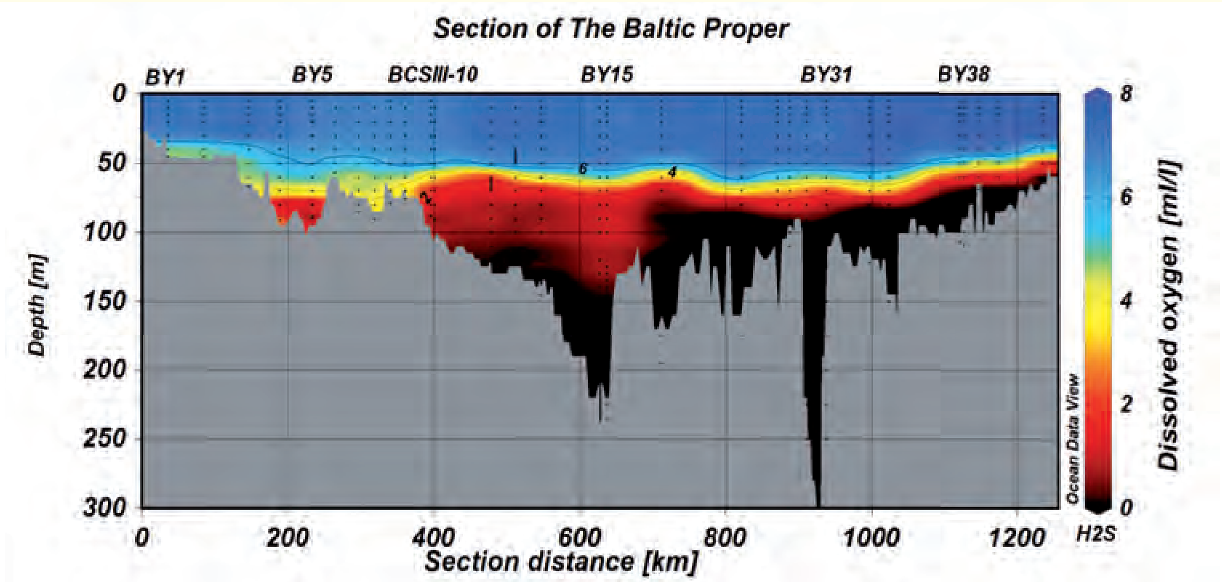

Figure 2.10. Section through the Baltic Proper (see red line in Figure 2.9 drawn after information at http://www.smhi.se/en/News-archive/oxygen-deficiency-in-the-baltic-sea-1.13992). The oxygen situation in the deep water of the Baltic Proper continues to be serious. The bad conditions measured during the beginning of the 21st century continue. About one-sixth of the bottom areas in the Baltic Proper were completely oxygen free, with toxic hydrogen sulphide present (Hansson et al. 2010).

Because of the restricted entrance for all basins, it is the excess evaporation versus precipitation that determines their present-day characteristics: because precipitation (from here on considered to include river inflow) exceeds evaporation for Baltic and Black Sea, both have an outflow of brackish water and a moderate but variable inflow of more saline water. This distinct density difference between surface and deep water results in a usually established stratified water column, which makes it more vulnerable to oxygen depletion.

For the present-day Mediterranean, evaporation exceeds precipitation, resulting not only in an eastward increasing salinity but also in a surface water inflow from the Atlantic, and a deep-Mediterranean outflow. The latter, anti-estuarine circulation system is known to result in a 'nutrient desert', thus low primary production, and consequently low

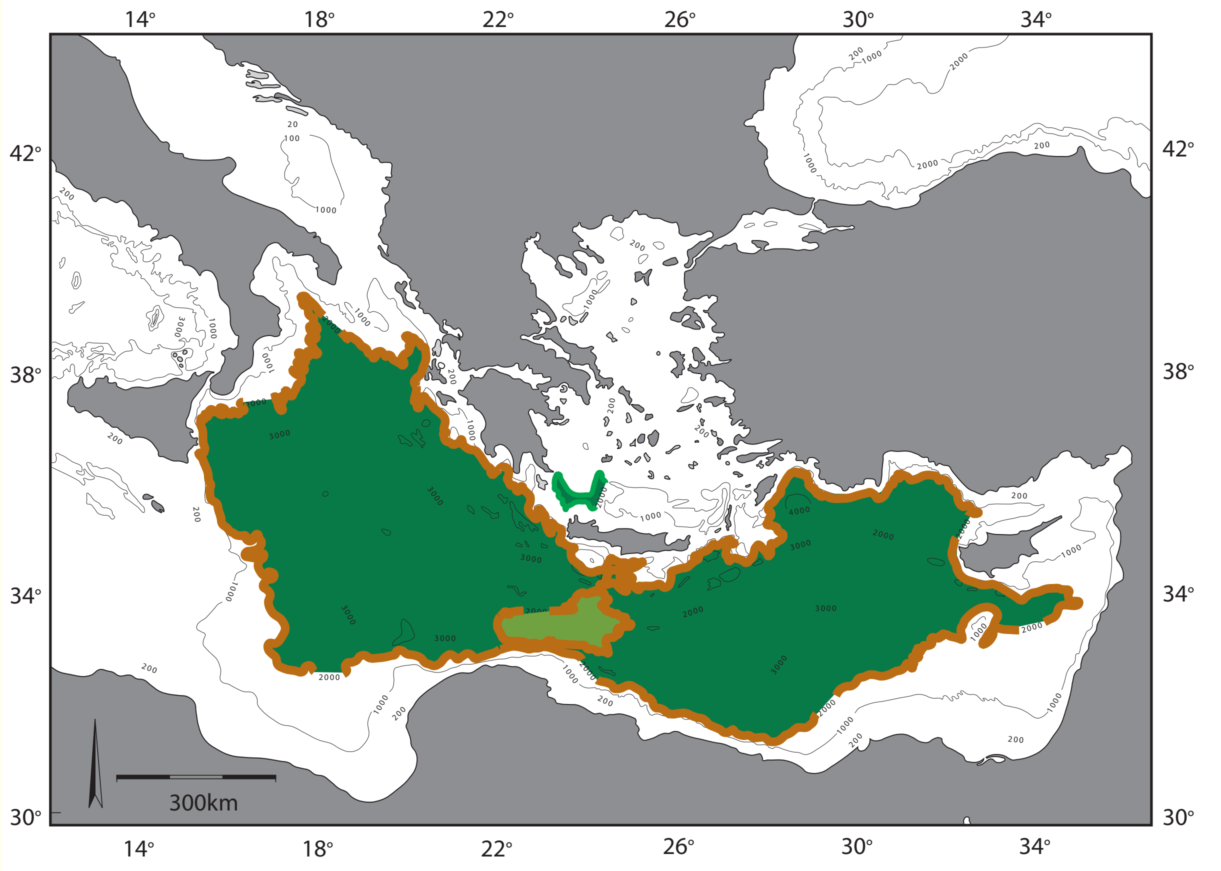

Figure 2.11. In green: water depths of more than 2 km, thought to have been (nearly) permanently anoxic during sapropel S1 formation (5.7-9.8 ka 14C BP). Brown border indicating approximately the 'bathtub ring' at 1.8 km with high sedimentary Mn content (up to 26 %) (De Lange et al. 2008).

oxygen consumption. Accordingly, the present-day Mediterranean is oxic until full water depths. The past anoxic episodes of Mediterranean deep water were always associated with enhanced rates of precipitation in line with climate changes, hence with an increased density gradient.

Clearly, if future climate-related changes in water budgets occur, this would have a major impact in particular on these vulnerable, restricted-circulation basins. On the one hand the excess usage of river water for irrigation has already resulted in a reduced river inflow into the Black Sea, whereas on the other hand a future change in precipitation patterns may significantly influence the functioning of each of these vulnerable basins.

Present Understanding

It is not clear yet in what direction future climate change will affect the regional and temporal precipitation rates and patterns for the Baltic, Black and Mediterranean Sea. The study of natural climate variability over the last 20 to 150 kyr may be helpful to detect such potential patterns of change. However, natural climate variability can mainly be studied for the Mediterranean basin, as the two others were merely freshwater lakes during the last glacial period. More information on the Baltic can be found in Conley et al. (2009), whereas a compact overview of the Black Sea is given by Murray et al. (2005), Murray et al. (2013).

Prominent precession-related Milankovitch climate cycles are well known and have been observed for the Mediterranean area to have occurred at least from the Miocene onward. The last precession-related humid climate period has been reported basin-wide from 10-6 ka (e.g., De Lange et al. 2008 and refs therein). During this period the Sahara was lushly vegetated, having lakes and the presence of humanoids (e.g., Gasse 2000). The basin-wide observed reduced surface water salinity during that period confirms the enhanced precipitation and is the origin for a hampered deep-water formation. The reduced deepwater ventilation and the concomitantly enhanced primary productivity have resulted in deepwater anoxia (e.g., Figure 2.11). Although the Black Sea is the largest anoxic marine basin in the present-day world, clearly the eastern Mediterranean was that for the early Holocene. Although during the most recent anoxic event the anoxic boundary is thought to have been at 1,800 m water depths, for several of the preceding humid events it has been reported that sulphidic, anoxic conditions occurred within the photic zone (e.g., Passier et al. 1999). The latter is thought to be as shallow as some 100 m. From physical oceanographic modelling experiments it is clear that it is not only the quantity of inflowing water (rivers, precipitation) that is relevant but also the region where and the period within which this occurs. Precipitation as determined by climate and climate-related shifts in the Inter Tropical Convergence Zone (ITCZ) seems to have a predominant influence.

Deepwater oxygenation may have important environmental implications. Deepwater ventilation controls redox conditions; the latter have a major impact on sedimentary nutrient (phosphate) regeneration. The enhanced release of phosphate will ultimately result in enhanced algal blooms in the surface waters, as has been reported for the recent Baltic and the early/mid Holocene Mediterranean (Conley et al. 2009, Jilbert et al. 2011 and refs therein, Slomp et al. 2002)

Future Perspectives

We have now briefly assessed that all three oceanic sub-basins discussed above are very vulnerable to climate change. Besides vulnerability related challenges, these basins can also be considered as excellent laboratories for studying large, e.g., regional- and temporal-scale biogeochemical processes. Not only can environmental/climate proxies be developed and validated, but also their sedimentary archives must be gold mines for studies in high-resolution natural climate variability. Thus, exactly because of their vulnerability to climate change, these European 'backyard' basins and in particular their sedimentary archives are for various aspects important targets of studies on high-resolution natural climate variability.

The take-home message

In particular an integrated, integrating, approach would be useful as each of the three basins contributed to different aspects not only in climate zones but also in environmental conditions. It is a perfect set of basins extending environmental conditions not only from oxic to anoxic, but also from low salinity (Baltic) to high salinity (Mediterranean), and having different ranges in temperature and nutrients supply. Consequently, any change will have an impact on the delicate balances for the Baltic, Black and Mediterranean seas that are highly sensitive to even subtle changes. Such impact will thus have a major effect on biological diversity and human use of these seas, including fisheries and recreation.

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Chapter 3

Dynamics of Ecosystems under Global Change

Eva Ramirez-Llodra

Planet Ocean

Our planet's surface is 71% water and 99% of its living biosphere is found in marine waters (Snelgrove 2010). It makes sense thus, as science-fiction writer Arthur C. Clarke pointed out, to rename our universal dwelling Planet Ocean (Figure 3.1). Fifty percent of our vast oceans lie below 3,000 m depth, with a mean depth of 3,800 m. Only a very small fraction of the open ocean and deep seafloor has been explored and investigated to date (Ramirez-Llodra et al. 2010). Nonetheless, what little we know provides evidence that the oceans are highly complex and dynamic systems that host a very high biodiversity and ecosystem functions that are crucial not only for the health of the planet, but also for the survival of humankind.

Ecosystem functions are the abiotic and biological processes that contribute to the maintenance of an ecosystem. The beneficial outcomes for the environment or society that result from ecosystem functions are called *ecosystem services* (UNEP 2007). The oceans are linked to the rest of the planet through exchanges of matter and energy and provide a whole host of important goods and services. These goods and services include (as adopted by the Millennium Ecosystem Assessment, MA, 2005) provisioning services (biological resources, mineral and hydrocarbon resources, genes and molecules with biotechnological and pharmaceutical uses, CO_2 capture and storage), ecosystem services (habitat, nutrient cycling, water circulation and exchange), regulating services (climate regulation, water purification and detoxification, biological regulation) and cultural services (recreation, sport, art) (Armstrong et al. 2012). In the last decades, the marine scientific community has focused on establishing a baseline

Figure 3.1. Planet Ocean © iStock

of knowledge about marine biodiversity, strongly accelerated during the Census of Marine Life programme (2000-2010) (reviews of the programme's achievements can be found in McIntyre 2010 and Snelgrove 2010). Marine ecosystems, their function and interconnectivity with the entire biosphere have also become a strong focus for academics. Interdisciplinary studies have shown that our planet is currently undergoing global changes that are already modifying ocean dynamics, structure and functioning of its ecosystems.

A changing ocean system

The future scenario of ocean acidification and global climate change will affect all marine areas, from the shallow inter-tidal to abyssal depths. A wide array of processes will be affected to varying degrees, including nutrient loading, stratification of water masses, hypoxia, circulation regime changes or warming temperatures amongst others. This global climate change will also have synergetic relationships with the impacts of waste disposal (chemical contamination and marine litter) and resource exploitation (fisheries, hydrocarbons and minerals), with yet unknown effects (Ramirez-Llodra et al. 2011). A good knowledge of biodiversity and ecosystem function and the response of marine communities to natural and anthropogenic change is essential to provide tools for all stakeholders (scientists, policy makers, industry and conservation organisations) to develop pathways to use and manage marine goods and services in the best possible way, taking into account these global changes.

Key topics in deep-sea and polar research

In the following five essays, marine scientists discuss key topics related to one or more functions provided by marine ecosystems in relation to global change, with a particular focus on the least explored areas of our Planet Ocean: the *deep sea* and the *polar seas*.

The first three essays in this chapter discuss fundamental aspects of deep-sea biodiversity and ecosystem function in relation to our changing planet. **Nadine Le Bris** opens with the first essay highlighting the importance of habitats, species and gene diversity of deep-sea systems. She advocates stronger synergetic relationships amongst scientists from different disciplines to address important gaps in our understanding of functioning in the deep sea. This topic is followed by essay two – a discussion led by **Marina R. Cunha** concerning ecosystem connectivity in the oceans, one of the major challenges faced by the marine scientific community to date. A good knowledge of connectivity is essential to elucidate the processes that lead to specific biogeographic and evolutionary patterns and to understand ecosystem responses to the increasing impact of human activities and global climate change. In the third essay, **Eva Ramirez-Llodra** and **Maria C. Baker** describe unique attributes of deep-sea ecosystems and the services they provide and engage the reader in an overview and discussion of current impacts faced by one of the last pristine biomes in Planet Ocean.

The last two essays focus on the effects of climate change in two particularly rich and vulnerable marine systems: polar seas and cold-water corals. Firstly, **J. Murray Roberts** debates on the other major global change currently occurring in the oceans: acidification caused by increasing anthropogenic CO_2 and its effects on cold-water corals. However, this essay goes beyond single-stressor impact and argues the need for multi-stressor studies that reflect the realistic scenario where ocean acidification, warming temperatures and additional anthropogenic activities (e.g., exploitation of resources or pollution) have mostly unknown combined effects on marine populations. Dr Roberts explains why multi-stressor experiments, powerful enough to probe for critical points where synergies between these stressors may cause significant phase shifts in ecosystems functioning, are urgently needed. In the final essay in this chapter, **Cinzia Verde** and **Guido di Prisco** draw our attention to the risks of cumulative effects of climate change for crucial polar ecoystem functions and propose a set of key questions that need to be addressed to develop predictive studies and management options integrating the multiple scales of biological organisation and function.

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Deep-sea biodiversity dynamics and ecosystem stability

Nadine Le Bris

Statement

While recent inventories (e.g., Census of Marine Life, McIntyre 2010, www.iobis.org) have revealed highly diverse, heterogeneous and fragmented deep seafloor habitats, the temporal dynamics of ecosystems at great depth remain largely unknown. The deep sea was long considered as remarkably stable but this paradigm is no longer supported (Glover et al. 2010). In contrast, numerous evidences of strong natural instabilities, such as those induced by volcanic eruptions on mid-ocean ridges and back-arc basins (Rubin et al. 2012), shaping benthic communities at deep-sea biodiversity hotspots have been reported (Mullineaux et al. 2009), Figure 3.2. Even meteorological events, like severe storms or wind-driven dense water cascading, can cause strong natural instability in the deep sea. They induce radical changes in the major macrofaunal species colonising these habitats, including commercial species (Sanchez-Vidal et al. 2007, Company et al. 2008). Although considered more stable, cold seep ecosystems are also exposed to natural disturbance from mud and gas extrusion events (e.g., Feseker et al. 2007).

Despite unprecedented efforts in the development of remotely operated vehicles and dedicated instrumentation, available tools to investigate ecosystems in the deep sea still provide very limited access to their dynamic patterns. As a consequence, little is known regarding the effects of extreme events and the transient response of ecosystems. Understanding the drivers of the stability of these ecosystems is crucial if we are to understand their capacity to respond to anthropogenic impacts, as well as their sustainability in a global change context that is likely to affect them.

Deep-sea biodiversity hotspots furthermore display unique environmental features, including steep variations in temperature, oxygen, pH, salinity, turbidity or toxicity. Deep-sea extreme environments therefore offer a mosaic of habitats where the balance between resource availability, tolerance to physico-chemical constraints, and

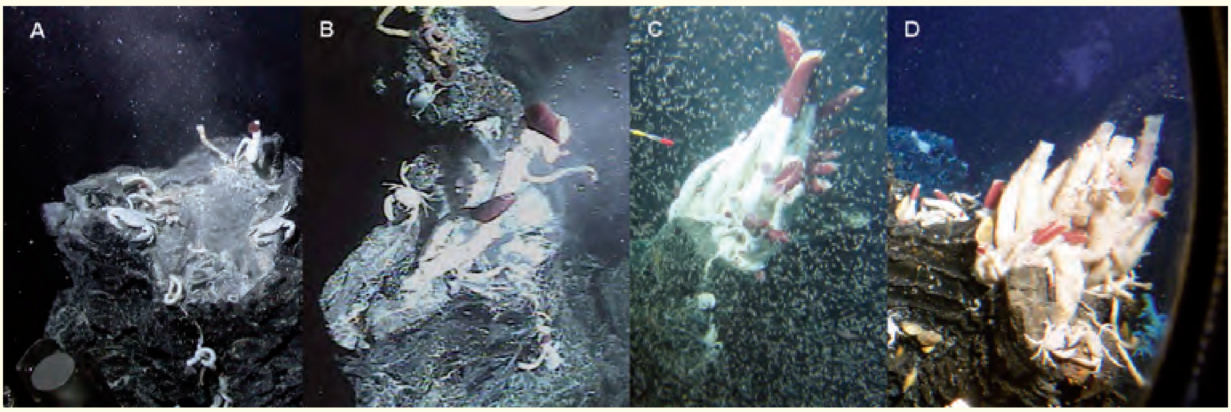

Figure 3.2. Re-colonisation of a diffuse vent after a lava flow at the 9°50'N site on the EPR: transition from microbial mats to symbiotic invertebrates. Images from January (A) and October (B) 2008 (WHOI, S. Sievert) and May 2010 (C) and Mars 2012 (D) (Ifremer, N. Le Bris).

dispersal capacity drives species dynamics. These ecological models are of particular relevance to investigate the links between benthic biodiversity and ecosystem functions in a dynamic perspective (CAREX Roadmap 2011).

Present Understanding

Deep-sea communities are adapted to take advantage of a wide variety of energy sources, ranging from reduced chemicals (methane, sulphide, hydrogen, metals) (Orcutt et al. 2011, Tunnicliffe 2003) to a variety of organic debris, from micrometre (Gage 2003, Smith et al. 2008) to tens of metres in size (Smith and Baco 2003). At depth, the dynamics of biological assemblages is dependent on these discontinuous energy sources, issued from surface waters or from the sub-seafloor. How the combination of chemoautrophic and heterotrophic energy pathways governs the dynamics of deep-sea communities is still mostly unknown. Except for some snapshot studies on production rates or inter-annual patterns of population dynamics for dominant symbiotic species, we know very little about the relationships between productivity and the diversity of key biological players.

Addressing the ecological functions of these communities requires synergies between scientists from different disciplines and particularly in marine ecology and biogeochemistry, but also in the fields of geosciences and physical and chemical oceanography. The knowledge acquired from those different fields remains very fragmented. Its integration is required prior to the definition of monitoring and conservation strategies.

Future Perspectives

A key to the understanding of processes governing ecosystem dynamics is better assessment and modelling of the interactions between biological, chemical and physical components of ecosystems. A number of key processes and main biological players are known, but the complex mechanisms driving their interplay in a temporal frame still need to be described. At larger scales, the dynamic interactions between different deep-sea ecosystems, at a meta-ecosystem scale, are unknown.

Conventional time series acquisition will still be necessary to document deep-sea biodiversity changes, but they will be efficiently complemented by unattended monitoring of chemical or physical key parameters and manipulative experiments on biological assemblages at dedicated sites. The context is particularly favourable with regular surveys being planned to monitor specific biodiversity hot-spots, as part of conservation programmes. At the same time, the energy supply and data transfer capacities of seafloor observatories will greatly enlarge the ability for continuous real time observation. Autonomous sensors are also becoming available for the design of experimental strategies (e.g., Mullineaux et al. 2012), and can be combined with molecular methods addressing the metabolic responses of organisms via gene or protein expression. These new omic tools offer promising approaches to study the interactions between species and their habitat (e.g., Garderbrecht et al. 2011, Sanders et al. 2013). Combination of multiscale approaches in modelling work is furthermore available from shallower ecosystems. All these novel opportunities are revolutionising the capacity to understand and predict the dynamics of ecological processes in the deep sea.

The take-home message

'Extreme' environments constitute unique natural models to understand the mechanisms driving the establishment and maintenance of biodiversity in deep-sea ecosystems. This concerns basic questions such as the role of biotic interaction in energy transfer (e.g., symbiosis, mutualism) as well as adaptation of species to a combination of abiotic stressors. It also addresses more complex systems including the colonisation dynamics in variable habitat conditions. Key issues that need to be addressed in the coming 10 years are:

- Relationships between energy sources and biodiversity (associations, mutualisms).
- Role of engineer species, recruitment dynamics and growth rates.
- Response to disturbance (metapopulation, metacommunities).

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Chapter 3

Ecosystem connectivity in a changing ocean

Marina R. Cunha

Statement

Ecosystem connectivity is crucial in sustaining the structure, function and productivity of ecosystems through the transfer of organisms, materials and energy. Connectivity has two components: the first component refers to the physical links between elements of the spatial structure of a landscape (often referred to as 'connectedness'); the second component is functional connectivity, a parameter of landscape function, which measures the processes by which sub-populations of organisms are interconnected into a functional demographic unit (Opermanis et al. 2012). This linkage between geographically separated populations (population connectivity) affects their structure and genetic diversity and plays an important role in local and metapopulation dynamics, species distributions, community dynamics and resilience to disturbance. Knowledge of connectivity is therefore essential to elucidate the processes that lead to specific biogeographic and evolutionary patterns and to understand ecosystem responses to the increasing impact of human activities and global climate change.

The lack of obvious boundaries and the vastness of the ocean led to the view of marine populations as demographically open (potentially at 100s to 1000s km scale). Over the past decades, accumulated scientific evidence led to significant paradigm shifts concerning connectivity (Cowen et al. 2006). In fact, marine invertebrates display a spectrum of reproductive strategies that are a major driving force influencing the degree of genetic differentiation and connectivity between populations. Dispersal potential may be highly variable and often limited by local hydrodynamics such that the potential gene flow of a species may never be realised fully. Also, temporal hydrographic changes can create significant spatial and temporal variability in recruitment and therefore it is possible for genetic disparity to occur at local (<1–10 km) as well as distant (100s to 1000s km) scales (Bell 2008).

Connectivity has taken centre stage with the widespread recognition of its implications for ecosystem health and ecological integrity. Furthermore, connectivity is crucial for the identification and implementation of technical options in applied problems in conservation management, such as the dynamics of infectious diseases, sustainable fisheries and the design of efficient networks of marine protected areas (MPAs). Systematic conservation planning aims to ensure that society 'has a plan' for conserving biodiversity and critical habitats in the face of impacts from activities and events that may alter the patterns and processes of natural ecosystems. However, the methods used to produce these plans originated 30 years ago (Groves et al. 2012), before the awareness that global environmental changes contribute to the observed declines in marine ecosystem health and fisheries harvests (Heyman and Wright 2011). Solutions to the global fisheries crisis must no longer focus simply on marine fisheries management interventions, or MPA designation focus solely on the protection of specific species and habitats. Connectivity is vital in the design of MPA networks because, by definition, populations/species protected by such networks should be connected through larval, juvenile or adult movement and connectivity describes these population linkages. A much more holistic approach to fisheries and spatially explicit marine management must recognise the vital importance of genetic diversity and connectivity for maintaining healthy marine ecosystems and enhancing their resilience to disturbance regimes characteristic of climate change.

Present Understanding

Marine dispersal is dominated by small spores and larvae with often long pelagic duration leading to low propagule concentrations making connectivity inherently difficult to measure. Fundamental knowledge of larval dispersal and connectivity can be gained from (1) understanding the biological and hydrodynamic processes involved in the transport of larvae and (2) deriving larval origins and dispersal pathways using geochemical, genetic or artificial markers (Cowen et al. 2006). Different but complementary methodologies are currently used for the investigation of connectivity in marine systems. Oceanographic models are excellent tools to study the transport of propagules between spatially discrete populations but they are seldom available and their application is severely hindered by our inadequate knowledge of the life-history strategies, survival and behaviour of the species. Empirical methods (e.g., molecular markers, micro-chemical fingerprinting) may give valuable insight on dispersal and the extent to which populations are connected. They are, however, often only feasible at limited spatial and temporal scales. Genetic indices of connectivity are invaluable for assessing gene flow and the evolutionary consequences of dispersal and they are frequently used to infer population connectivity. However, reliance on genetic methods alone will not provide adequate information on the demographic aspects of connectivity. Micro-chemical fingerprinting may be the currently available method most suitable to determine natal origin of individuals within a population and for discriminating between local and immigrant recruitment, but its full potential application awaits further methodological clarification.

Irrespective of how connectivity is estimated, it is presently not clear how to include this information in algorithms for MPA selection. However, the progress in biophysical modelling can offer a framework for optimal selection of MPA networks based on connectivities, which should improve guidelines for the design of functional MPA networks (Berglund et al. 2012). Recent studies showed that connectivity may be more important than habitat quality as a selection criterion for MPA networks when targeting species with long-distance dispersal that is typical for many marine invertebrates and fish. The same studies showed that optimal solutions of MPA networks converged when based on 8–10 years of connectivity information, corresponding to the time scale of the North Atlantic oscillation (Berglund et al. 2012). Genetic analysis suggest that island MPAs may not provide as much larval export or receive as much buffering against local extinctions, compared with mainland populations. Low levels of larval exchange may limit the success of any protected area, preventing multiple conservation objectives from being achieved. This type of data is especially informative to the creation of MPA networks (Bell 2008).

Even in the absence of climate change, connectivity is considered important to prevent isolation of populations and ecosystems, provide for species with large home ranges, provide for access of species to different habitats to complete life cycles and to alleviate problems deriving from multiple metapopulations that are below viability thresholds (Groves et al. 2012). Today, we lack a complete understanding of exactly what types and locations of connectivity are needed to enable climate change-induced species movements, and whether they are similar to or different from connectivity needs under current climate conditions (Groves et al. 2012).

Future Perspectives

How metazoans colonise and disperse between sometimes distant habitats is not yet fully understood. Documenting reproductive and larval development traits (e.g., planktonic larval duration – PLD, mortality and behaviour) (Metaxas and Saunders 2009), dispersal strategies, colonisation and ultimately connectivity among populations is mandatory if we are to understand biodiversity, ecological integrity, biogeographic patterns and evolution. Under a climate change scenario, understanding the types and patterns of connectivity is of utmost importance as many species and communities may respond to climate change by shifting their geographical distributions. There is an urgent need to incorporate information on connectivity and environmental change and update conservation planning to improve the chances that these plans and priorities will remain effective in achieving the greatest ecological and societal benefits as climate changes.

Identified research priorities and strategies for an organised effort in growing connectivity research may be summarised under the following points:

Technological developments: a diverse array of complementary techniques is needed to address connectivity. Some of these techniques are available but require improved application; others have yet to be developed. One important step will be to develop new modelling applications in parallel with the validation and iterative improvement of bio-physical models by complementary empirical methodologies (e.g., genetic tools and micro-chemical fingerprinting, tracers and 'smart' drifters). Developing innovative sampling gear and sensors is crucial to improve the efficiency of the collection of representative life-stages and environmental data at relevant spatial and temporal scales. The efforts to upgrade molecular tools (e.g., ISH second generation sequencing) and further develop *in situ* (Figure 3.3) and *ex situ* experimental approaches must also be continued and reinforced.

Multidisciplinary teams: tackling the complex issues of connectivity will involve bringing together expertise in ecology, genetics, physical oceanography, applied mathematics, computer science, policy and management. It is essential to assemble the international scientific community in well-coordinated multidisciplinary teams with a size and scope capable of reversing the current research limitations.

Integrated observations: the multiple spatial and temporal scales in which connectivity operates require standardised methodologies for process-oriented data collection for local short-term application but that can be replicated over large spatial scales (basin wide) and integrated with sustained long-term observatory systems and eventually permanent observatories. Strategic actions may further include the promotion of international programmes for shared use of facilities, ship-time, specialised equipment and databases.

Translating science into societal issues: a persistent challenge for marine scientists is to improve communication with conservation managers, stakeholders, science policy researchers and decision makers. This can be achieved largely by the inclusion of these agents as active team members, but mostly by valuing the societal implications of connectivity research and providing the relevant scientific information in a community-accessible language.

Figure 3.3. *In situ* colonisation experiments recovered by the ROV in the Gulf of Cadiz during the RV *Belgica* cruise B09 in the framework of the CHEMECO Consortium (EuroDEEP/ESF).

The take-home message

Connectivity acts at multiple temporal and spatial scales and it recognises no political borders. The inability to accurately predict dispersal and the lack of knowledge of the types and patterns of connectivity make it impossible to determine the effect of climate change and/or human exploitation on marine ecosystems.
Resolution of this problem must be achieved through a concerted effort of multidisciplinary international teams and it will have a relevant impact on our knowledge of biogeography and evolution, as well as direct applications in the management of marine resources with indisputable societal benefits.

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Deep-sea biodiversity, ecosystem function and ecosystem services on our changing planet

Eva Ramirez-Llodra – Maria C. Baker

Statement

The largest ecosystem on Earth, the deep ocean, is also the least explored and understood. The oceans cover 71% of the planet's surface, with 50% below 3,000 m depth and a mean depth of 3,800 m. Only 5% of the deep sea has been explored with remote instruments and less than 0.0001% of the deep sea floor (the equivalent of a few football fields) has been directly sampled and studied in any detail. The deep ocean hosts a wide diversity of geological and ecological settings that might not be apparent to the casual observer sailing across the surface of these deep waters. Considering Forbes' dredging cruise in 1842 as the start of deep-sea research, 22 new deep-sea habitats and ecosystems have been discovered in the past 170 years (Figure 3.4). This is an average of one new habitat every eight years (Ramirez-Llodra et al. 2010).

Of the 510 million km^2 of Earth's surface, 362 million km^2 are ocean sea floor, roughly 90% of sea floor is below 200 m – generally considered 'deep sea'. The deep sea floor is formed by hundreds of millions of km^2 of continental slope and abyssal plains. Embedded within these slopes and deep basins are other biological and geological structures, including mid-ocean ridges, canyons, seamounts, cold-water corals, hydrothermal vents, methane seeps, mud volcanoes, faults and trenches, which support unique microbiological and faunal communities. Biological structures also provide substantial habitat for other sea life such as cold-water coral reefs and sponge beds. The deep-sea pelagic environment is even larger, adding a third dimension. The latest estimate for the total volume of our oceans is 1.3324 X 10^9 km^3 (Charette and Smith 2010), and the vast majority of this volume is at depth.

What little we know of this vast environment provides evidence that there are major abiotic and biotic characteristics that make the deep sea a unique environment (reviewed in Ramirez-Llodra et al. 2010). For example, biodiversity is extraordinarily high in deep-sea sediments (Rex and Etter 2010). In addition, many fish and invertebrates inhabiting the deep ocean are long-lived and slow-growing species with episodic recruitment and late-onset maturity, making these living resources extremely susceptible to over-exploitation. Conversely, animals living at hydrothermal vents are among the fastest growing animals known and relatively low biodiversity exists in these systems. Deep-sea biodiversity supports a wide range of key ecosystem functions – the abiotic and biological processes that contribute to the maintenance of an ecosystem. Ecosystem services are the beneficial outcomes, for the environment or society, which result from ecosystem functions. The deep sea can provide a whole host of important eco-

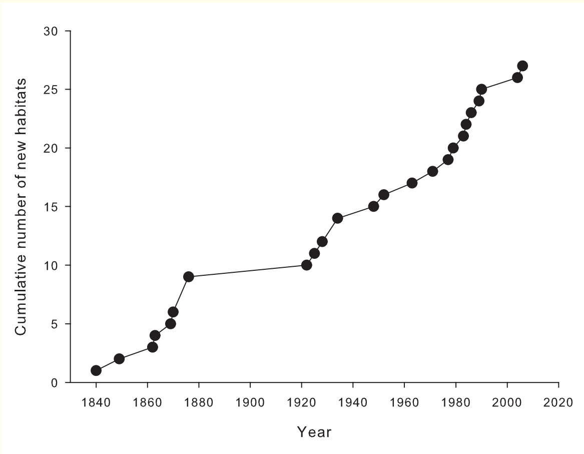

Figure 3.4. Habitat discovery rate from Forbes' Azoic theory to date. Figure from Ramirez-Llodra et al. *Biogeosciences*, 7, 2851–2899 (2010).

system services, which include supporting services, provisioning services, regulating services and cultural services (Armstrong et al. 2012, Thurber et al. 2014) (see below for details).

Baseline knowledge of deep-sea systems is essential to the effective management of the rich mosaic of habitats and ecosystems that support such diverse life in our ocean depths. The system is complex and the functioning of deep-sea ecosystems is crucial to global biogeochemical cycles (Cochonat et al. 2007, Jorgensen and Boetius 2007, Danovaro et al. 2008) upon which much terrestrial life, including human civilisation, ultimately depends. As we begin to understand more about this complex interconnectivity and the regulating and supporting services the deep sea provides, along with the increased accessibility of the rich pickings to be had in terms of provisioning services, the perception of this ocean realm is changing. Today, deep-sea scientists have the huge challenge of trying to fill the important scientific gaps that exist in our fundamental knowledge of deep-sea biodiversity and ecosystem function so that this essential information may drive management of human activities ensuring long-term effectiveness.

Current Knowledge

A number of physical, geological, chemical, biological and ecological characteristics make the deep sea a unique environment. Some of the most important patterns and processes of deep-sea systems are highlighted below (from Ramirez-Llodra et al., 2010):

- The lack of photosynthetically-usable sunlight approximately below 200 m results in a lack of primary production in most deep-sea ecosystems, with the exception of reducing deep-sea habitats (e.g., hydrothermal vents and cold seeps) where chemosynthetic microorganisms play the role of primary producers.
- Deep-sea benthic communities are amongst the most food-limited on the globe (Smith et al. 2008), yielding low faunal biomass and productivity (Rex et al. 2006, Rowe and Kennicutt 2008), except in chemosynthetically-driven ecosystems and beneath upwelling regions.
- Deep-sea diversity is among the highest on Earth (Hessler and Sanders 1967, Snelgrove and Smith 2002, Rex and Etter 2010). Although not universal, many deep-sea communities follow a unimodal diversity-depth pattern (Rex 1981), a poleward trend of decreasing diversity, and high evenness (Gage and Tyler 1991, Flach and de Bruin 1999) except in habitats where 'extreme' environmental factors (e.g., vents, seeps, OMZs) force high dominance of a few specially-adapted species.
- Although no invertebrate phyla are exclusive to deep-sea ecosystems, at lower taxonomic levels several otherwise rare groups of animals and abundant large protozoans dominate biomass, energy flow and biodiversity patterns in deep-sea sediments.
- The interconnected nature of the deep sea, the small sampling coverage achieved to date and the paucity of species descriptions make taxonomic coordination particularly difficult but especially important in understanding large-scale (regional and global) diversity patterns (Mora et al. 2008).

The inaccessibility of the deep sea and the subsequent requirement of advanced technologies and expensive operations have kept this ecosystem virtually unknown to most people with the exception of a few researchers funded by a subset of wealthy nations over the past couple of decades. As a result, natural or anthropogenic impacts in the deep sea are not addressed at the same level as processes of similar magnitudes on land. With the depletion of resources in shallower waters, industries such as fisheries, hydrocarbon exploitation and marine mining are increasingly exploring deeper systems, with activities now regularly surpassing 2,000 m depth (UNEP 2007). However, the effects of anthropogenic impacts on deep-sea habitats and communities are still mostly unknown and difficult to predict.

Although deep-sea services were mostly unknown only two decades ago, recent explorations and scientific research have increased our awareness of our dependency on these remote ecosystems (Thurber et al. 2014). In Europe, two FP7 projects (HERMES and HERMIONE) have addressed the issue of ecosystem goods and services in deep European waters (UNEP 2007, Armstrong et al. 2012). Currently, international programmes such as International Network for Scientific Investigations of Deep-Sea Ecosystems (INDEEP) (http://www.indeep-project.org/), Deep-Ocean Stewardship Initiative (DOSI) (http://www.indeep-project.org/deep-ocean-stewardship-initiative) and Global Ocean Biodiversity Initiative (GOBI) (http://www.gobi.org/) are actively engaged in the study of deep-sea ecosystem biodiversity, function and services. Below, the different services provided by the deep sea are described (Armstrong et al. 2012, Thurber et al. 2014).

Supporting Services

- *Habitat:* the deep sea is the largest ecosystem on Earth, providing a home to 98% of all marine species and the variety of habitats results in a wealth of adaptations in unique organisms.
- *Nutrient cycling*: the biogeochemical processes conducted by the deep-sea microbial component are essential to sustain primary and secondary production in the oceans, driving nutrient regeneration and global biogeochemical cycles (Arrigo 2005).
- Water circulation and exchange: the global movement of water masses is essential for ocean productivity. Deep-water formation in certain areas of the planet ensures oxygenation and upwelling systems provide nutrients to surface waters.
- *Chemosynthetic ecosystems:* in some cold seep areas, methane absorption by methanotrophic microorganisms prevents the entrance of part of the methane emitted by the habitat, providing a filter against this active greenhouse gas.
- *Resilience*: In general, highly biodiverse ecosystems have a higher resilience because of their capacity to maintain ecosystem functions under unpredictable changes. The deep sea contributes greatly to both terrestrial and marine resilience by playing an important role (amongst others) in carbon sequestration and temperature regulation.

Provisioning Services

- *Fisheries:* biological resources are being exploited commercially below 2,000 m depth.
- *Hydrocarbons and minerals:* oil and gas are major resources exploited in marine systems, with exploration wells being drilled down to 3,000 m depth.
- *Bioprospecting*: The deep sea is the largest reservoir of genetic resources and biological substances that include important chemical compounds of biotechnological interest for pharmaceutical, medical and industrial uses.
- *Waste disposal*: the deep sea has been used in the past for the disposal of wastes such as sewage sludge, dredge spoil, radioactive waste, dumping of dangerous warfare munitions and chemical weapons, as well as for the disposal of large structures such as ships and oil rigs. This routine disposal of waste into the oceans was legally banned in 1972 by the London Convention, followed by a stricter convention that entered into force in 2006. However, litter continues to enter the oceans daily from the coastal areas, river outflows and illegal dumping from ships, with 6.4 million tonnes of litter entering the oceans every year (UNEP 2009).
- *CO_2 capture and storage*: methods proposed for the long-term disposal of greenhouse gases include both sub-seabed disposal and surface seabed disposal, based on the principle that the injection of CO_2 into suitable seabed structures (including past and ongoing oil and gas reservoirs) should cause the CO_2 to form hydrates and hence act as a long-term depository of excess CO_2.

Regulating Services

- *Gas and climate regulation:* the biological pump recycles nutrients providing food for deep-dwelling species and plays a crucial role in the Earth's carbon cycle and its ultimate burial in deep-sea sediments. This natural process of carbon sequestration and storage in the deep sea plays an important role in climate regulation.
- *Waste absorption and detoxification*: the transport of waste and toxic chemicals down-slope and subsequent burial and transformation by organisms through assimilation and chemical transformation, either directly or indirectly.
- *Biological regulation:* these are the services that result from interactions between species or genotypes and they are directly linked to biodiversity.

Cultural Services

The deep sea provides educational, scientific and knowledge services, although the value of these services is difficult to calculate. The aesthetic services of the deep sea are difficult to evaluate, because of the remoteness of the system, but there is an increasing number of illustrated and educational books that provide an indirect vision of this hidden world. Finally, in several societies, certain deep-sea creatures play an important role in spiritual life.

Future Perspectives

In the last decades, decreases in the amount of land-based and coastal resources combined with rapid technological development has driven increased interest in the exploration and exploitation of deep-sea goods and services, to advance at a faster pace than the acquisition of scientific knowledge of the ecosystems (Ramirez-Llodra et al. 2011). A study by Halpern et al. (2008) indicates that no area in the

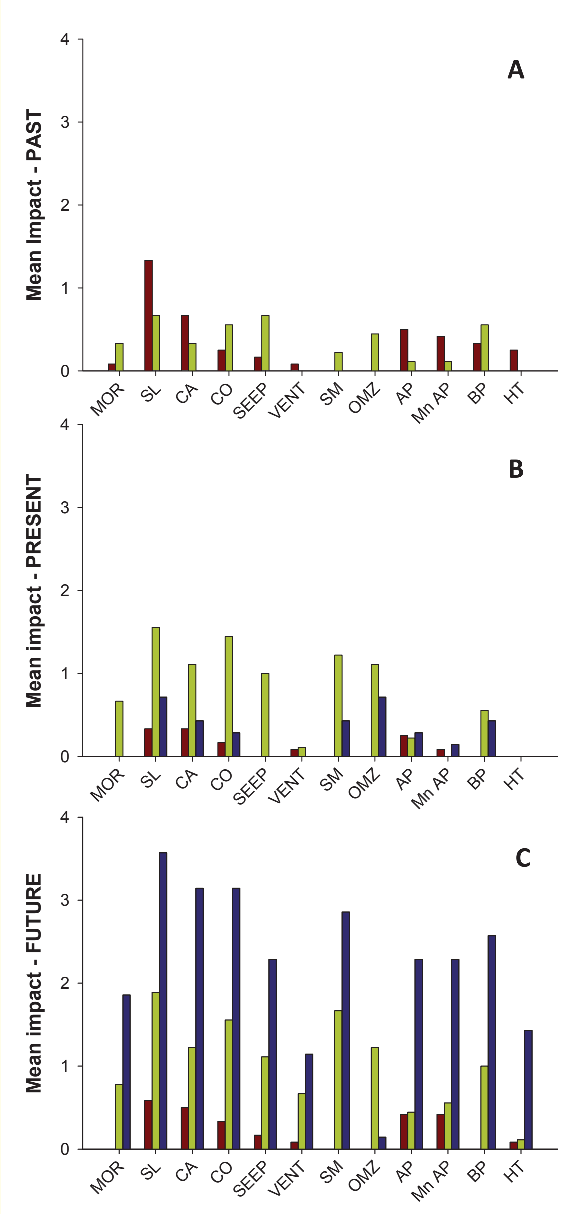

Figure 3.5. Evolution of the dominant impacts on deep-sea habitats. Mean levels of estimated impact for disposal (red bars), exploitation (green bars) and climate change (blue bars) in past (A), present (B) and future (C) scenarios. Levels of impact estimated from Table 1. MOR, mid-ocean ridge; SL, sediment slope; CA, canyons; CO, corals; SEEP, cold seeps; VENT, hydrothermal vents; SM, seamounts; OMZ, oxygen minimum zones; AP, abyssal plains; Mn AP, manganese nodule abyssal plains; BP, bathypelagic; HT, hadal trenches. Figure from Ramirez-Llodra et al. *PLOS ONE* 6(8): e22588 (2011).

ocean is completely unaffected by anthropogenic impact and that 41% of ocean areas are affected by multiple drivers, with coastal ecosystems receiving the greatest cumulative impact, while Polar regions and deep waters are the least impacted. Recent studies have highlighted the vulnerability of deep-sea ecosystem functioning to biodiversity loss (Danovaro et al. 2008). Understanding the present threats to deep-sea biodiversity is therefore crucial for a sustainable management of deep-sea ecosystems and their resources. One of the major limitations to developing robust conservation and management options is the relatively small amount of information available on deep-sea habitat distribution, faunal composition, biodiversity and ecosystem functioning (UNEP 2007).

Ramirez-Llodra et al. (2011) reviewed known anthropogenic impacts on deep-sea ecosystems and their effects on the habitat and fauna. The analysis was conducted in past and present scenarios and predictions were made for mid-term future scenarios. The analysis shows that the overall anthropogenic impact in the deep sea is increasing and that the most significant activities have evolved from disposal (past) to exploitation (present) (Figure 3.5). The authors predict also that increases in atmospheric CO_2 and facets and consequences of climate change will have the most impact on deep-sea ecosystems, affecting the habitats and their fauna globally. Synergies between different impacts are also important and need to be taken into account. Because increased atmospheric CO_2 and climate change, together with associated effects such as warming, primary production shifts, ocean acidification and hypoxia, affect the oceans globally, this is where most synergistic processes will occur (Figure 3.6), sometimes with positive feedbacks that increase greenhouse effects.

Based on current knowledge of deep-sea biodiversity, functioning and human use and predictions on the development of industrial activities and potential effects of climate change, a series of deep-sea ecosystems can be identified, believed to be at higher risk from human impacts in the near future: 1) benthic communities on sedimentary upper slopes, 2) cold-water corals, 3) canyon benthic communities and 4) seamount pelagic and benthic communities (Ramirez-Llodra et al. 2011). However, to date little information is available on the direct and long-term effects of human activities in bathyal and abyssal ecosystems and, in particular, on their fauna. The deep-water ecosystem is poorly understood in comparison with shallow-water and land areas, making environmental management in deep waters difficult. A further difficulty for management is the fact that large areas of the deep sea are under international waters. Deep-water ecosystem-based management and governance urgently need extensive new data and sound interpretation of available data at the regional and global scale as well as studies directly assessing impact on the faunal communities.

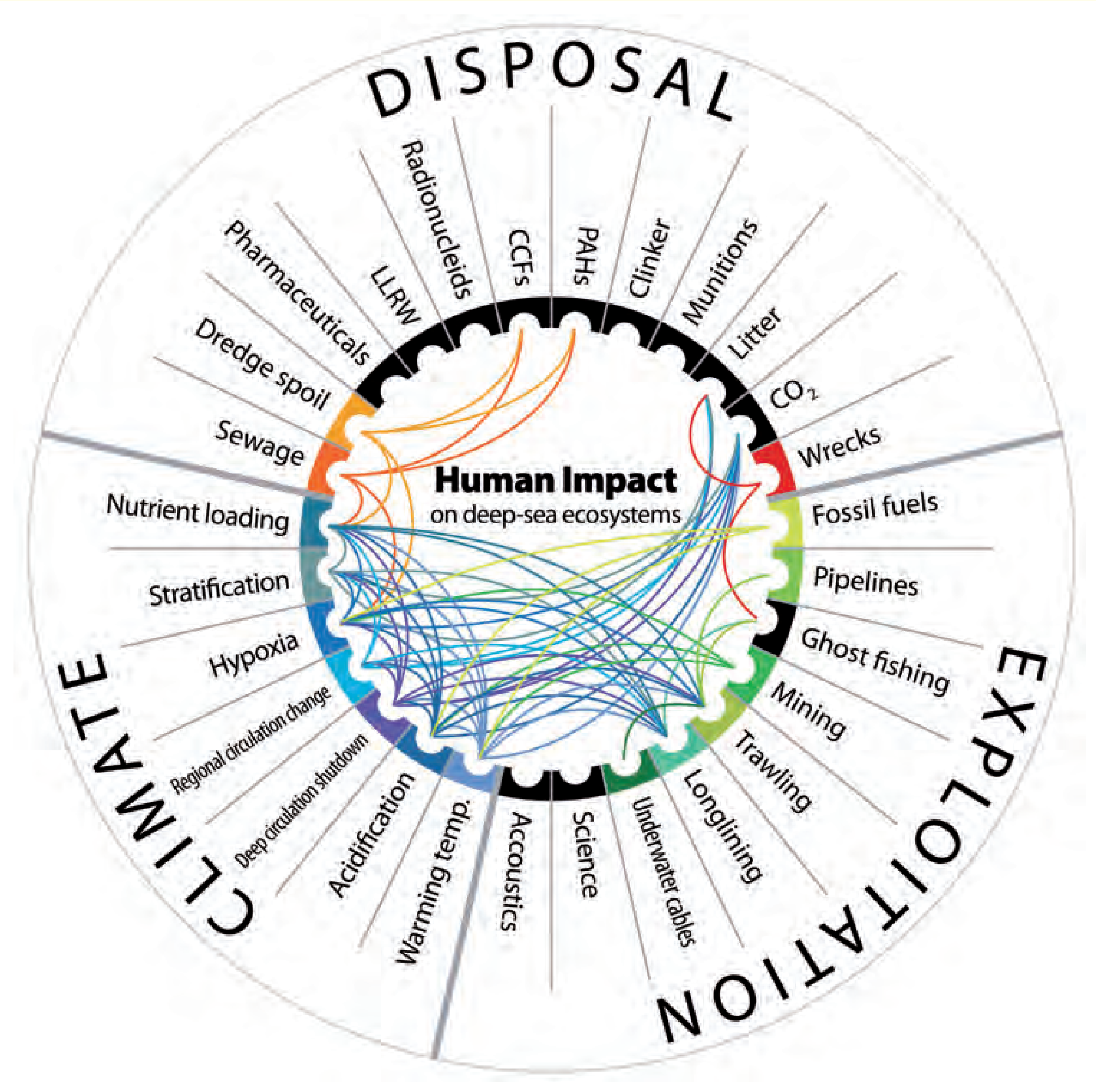

Figure 3.6. Synergies amongst anthropogenic impacts on deep-sea habitats. The lines link impacts that, when found together, have a synergistic effect on habitats or faunal communities. The lines are colour coded, indicating the direction of the synergy. LLRW, low-level radioactive waste; CFCs, chlorofluorocarbons; PAHs, polycyclic aromatic hydrocarbons. Figure from Ramirez-Llodra et al. *PLOS ONE* 6(8): e22588 (2011).

The take-home message

The deep sea is the largest ecosystem on Earth but also one of the least known. What little we know provides evidence of very high biodiversity levels as well as important ecosystem functions and services. The increasing use of deep-sea services is thus affecting ecosystems before we have a good understanding of their biodiversity and function. Additionally, the global changes related to ocean acidification and climate change can have important synergies of yet unknown consequences with other anthropogenic impacts on deep-sea habitats and fauna. It is thus urgent that we continue to explore and study these remote systems under interdisciplinary and ecological approaches. It is also imperative that natural scientists work together with other stakeholders, including social scientists, industry, economists, lawyers, policy makers and NGOs to develop efficient ecosystem-based management of resource use in the deep ocean that will ensure the maintenance of the integrity of deep-ocean ecosystems, their biodiversity, function and services.

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Chapter 3

The response of reef framework-forming cold-water corals to ocean acidification

J. Murray Roberts

Statement

Corals are not restricted to shallow, tropical coral reefs. Since the late 1990s, research into the coral habitats found in deeper waters on seamounts, continental shelves, slopes, offshore banks and in fjords has increased exponentially (Roberts et al. 2009). These cold-water coral habitats include deep-water biogenic reefs formed by a small group of hard (scleractinian) corals whose colonies form complex three-dimensional frameworks (Roberts et al. 2006). Cold-water coral frameworks produce intricate structural habitats that trap mobile sediments and provide niches for many other species (Figure 3.7). For example, in the Porcupine Seabight (SW Ireland), approximately three times more species were found in samples from coral carbonate mounds compared to neighbouring off-mound areas (Henry and Roberts 2007).

Figure 3.7. A greater forkbeard fish (*Phycis blennoides*) swims above the dense cold-water coral reef framework on the Logachev Mound Province (Southern Rockall Bank, NE Atlantic). Image courtesy of Heriot-Watt University 'Changing Oceans Expedition 2012', RRS *James Cook* cruise 073, UK Ocean Acidification programme (sponsors: NERC, DECC, Defra).

Scleractinian corals build their skeletons from aragonite, one of the most soluble forms of calcium carbonate. Since these calcium carbonate skeletons can be accurately dated, there is a growing understanding of cold-water coral ecosystem history. The ubiquitous coral *Lophelia pertusa*, which forms the majority of Atlantic deep-water reefs, flourished at high latitudes in interglacial periods, but was absent during glacial climates. There is good evidence that these corals rapidly recolonised as glacial conditions receded (Frank et al. 2009), as shown by the re-appearance of *L. pertusa* at 70°N in the early Holocene 10.9 kya (López-Correa et al. 2012).

Unlike shallow tropical corals, cold-water corals do not contain photosynthetic symbionts and, instead, rely entirely on feeding from the water column. Detailed studies of the hydrographic regimes around cold-water reefs have begun to unravel the mechanisms that supply food to these diverse biological communities (Davies et al. 2009). In addition, habitat suitability modelling approaches have begun to show not just what areas might be suitable for coral growth, but also what characterises the niches these corals require (Tittensor et al. 2009). Thus it has become clear that corals in deep waters are closely tied to specific local environmental and food supply conditions and over millennia their success or failure correlates closely with global climatic cycles. But what is understood of their potential vulnerability to anthropogenic climate change?

Present Understanding

Greenhouse gas emissions are changing the planet's climate at an unprecedented rate, with global warming a now widely recognised phenomenon. It is estimated that over the last 40 years >80% of global heating processes have gone into warming the oceans (Levitus et al. 2005) and that this warming signal can be detected to depths of at least 700 m (Barnett et al. 2005). As marine ecosystems warm, some shallow-water species have already shifted their distributions to regions that were previously unsuitable (Mieszkowska et al. 2006). But in deep waters, the implications of ocean warming remain hard to observe and very poorly understood. Where examples exist, some dramatic changes have been recorded such as the mass mortality of precious corals (*Corallium rubrum*) in the Mediterranean following the increased summer temperatures of 1999 and 2003 (Torrents et al. 2008). Few studies have examined the physiological response of cold-water corals to temperature change, but there is evidence that over short periods at higher temperatures *L. pertusa* shows a marked increase in metabolic rate that would require increased food input (Dodds et al. 2007). Without this increased food input, or the ability to acclimate, this implies that *L. pertusa* would starve under prolonged elevated temperatures and, therefore, the reefs it produces would degrade. Recent longer-term work on Mediterranean cold-water corals *Dendrophyllia cornigera* and *Desmophyllum dianthus* suggests that these species may be able to adapt to higher experimental temperatures (Naumann et al. 2013).

But anthropogenic CO_2 does not only contribute to planetary warming. Approximately a third of the CO_2 released since the Industrial Revolution has dissolved in the oceans of the world. While this has mitigated atmospheric warming, it has led to the so-called 'evil twin' of global warming – ocean acidification (CBD 2014). When CO_2 dissolves in seawater, a series of chemical equilibria are affected, leading to the generation of hydrogen ions and a consequent lowering of pH:

$$CO_2 + H_2O \Leftrightarrow H_2CO_3 \Leftrightarrow HCO_3^- + H^+ \Leftrightarrow CO_3^{2-} + 2H^+$$

The scientific community's understanding of ocean acidification is based upon a well-developed knowledge of seawater carbonate chemistry, but a much more limited understanding of how these changes will affect marine ecosystems. Of all marine organisms, those that rely on skeletons formed from calcium carbonate, including the corals, would appear amongst the most vulnerable to ocean acidification (Wicks and Roberts 2012). Corals calcify

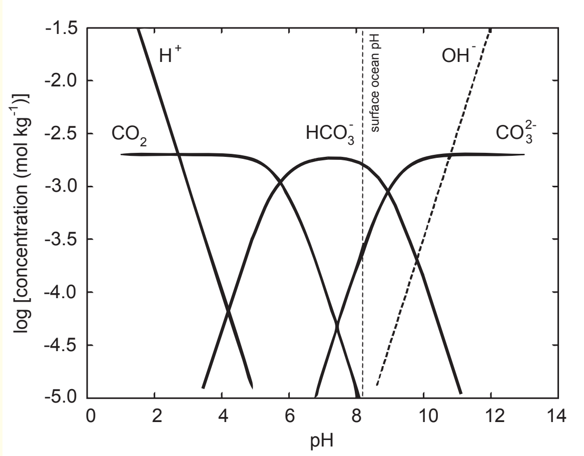

Figure 3.8. Bjerrum plot showing typical concentrations of dissolved carbonate species in seawater as a function of pH. Figure redrawn from Zeebe and Gattuso (2006).

by bringing together ions of calcium and carbonate together in a locally supersaturated solution that promotes calcium carbonate mineral crystals to form in a structured way. While the precise nature of the calcifying space and mechanism remain debated, the chemical equilibria are well understood and corals are believed to elevate pH where they deposit skeletal material in order to favour calcification.

$$Ca^{2+} + 2HCO_3^- \Leftrightarrow CaCO_3 + CO_2 + H_2O$$
$$Ca^{2+} + CO_3^{2-} \Leftrightarrow CaCO_3$$

At the pH of pre-industrial seawater (8.2), 89% of the Dissolved Inorganic Carbon (DIC) was present as bicarbonate (HCO_3^-), 10.5% as carbonate (CO_3^{2-}) and 0.5% as dissolved carbon dioxide (CO_2). As pH declines, the concentration of bicarbonate remains relatively unchanged, whereas the concentration of carbonate rapidly declines (Figure 3.8). It is this change in carbonate ion concentration that lies at the heart of concerns over the impact of ocean acidification on marine calcifiers.

The present day changes in seawater chemistry are now being recorded in long-term monitoring stations around the world. Although marine carbonate chemistry shows considerable variation, the trends recorded from monitoring beginning in the mid-1980s are very clear: as the partial pressure of CO_2 in seawater increases, there is a corresponding drop in pH (Figure 3.9).

The global trend of rising oceanic pCO_2 and declining pH has far reaching implications. In terms of deep-water organisms it is necessary to understand how these changes alter the chemistry of seawater at depth. To date, there has been no long-term continuous monitoring of deep-sea carbonate chemistry and our understanding of potential changes relies on sparse measurements

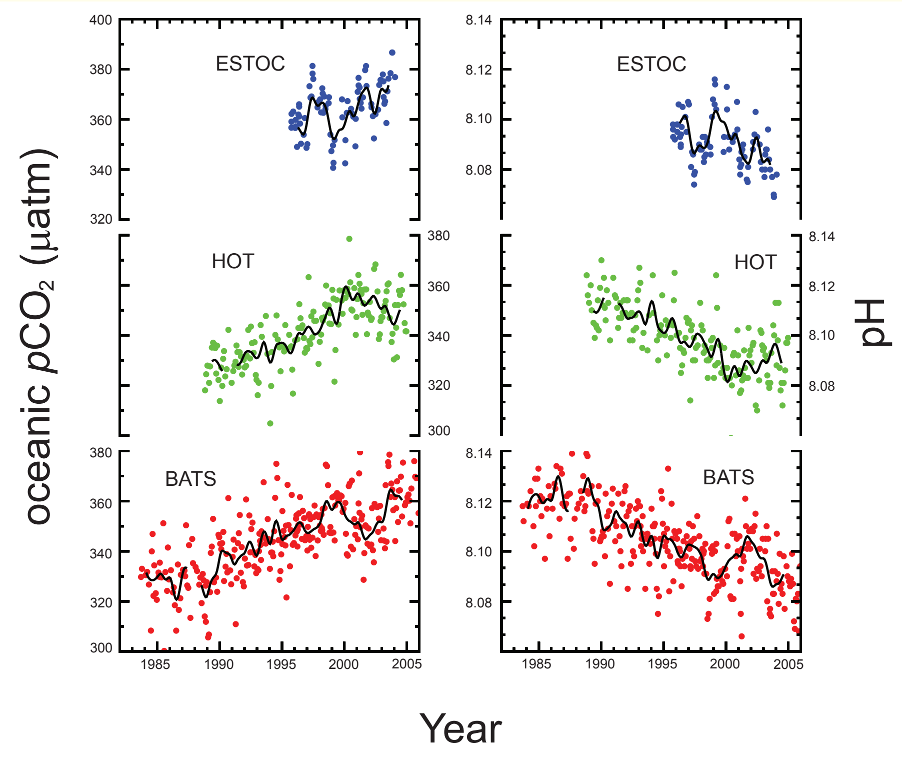

Figure 3.9. Changes recorded in surface ocean pCO_2 (left) and pH (right) from three time series stations: European Station for Time-series in the Ocean (ESTOC, 29°N, 15°W); Hawaii Ocean Time-Series (HOT, 23°N, 158°W); Bermuda Atlantic Time-series Study (BATS, 31/32°N, 64°W). Values of pCO_2 and pH were calculated from DIC and alkalinity at HOT and BATS; pH was directly measured at ESTOC and pCO_2 was calculated from pH and alkalinity. The mean seasonal cycle was removed from all data. The thick black line is smoothed and does not contain variability of less than a six month period. Figure reproduced from Figure 5.9 (p. 404) in Bindoffet al. (2007).

and modelled predictions. Evidence of anthropogenic CO_2 has been detected at depths of up to 2500 m and is thought to have penetrated to at least 5,000 m (Feely et al. 2001, Tanhua et al. 2007). In 2005, Orr et al. presented a modelled simulation of the effects of CO_2 release on the carbonate saturation state of the oceans. This model showed that, under the IPCC 'business as usual' scenario (IS92a) where little is done to mitigate CO_2 emissions, the depth of the aragonite saturation horizon (ASH) would rapidly shoal in the 21st century. This meant that virtually all of the Atlantic's cold-water corals would become exposed to undersaturated seawater (Guinotte et al. 2006), and exposed dead coral skeletons would therefore begin to dissolve, potentially destroying deep-water reef structure (Roberts et al. 2006, Turley et al. 2007).

Measurements now show that in the North Pacific the ASH has already shoaled by 50-100 m (Feely et al. 2008) and, given that the rates of anthropogenic CO_2 release are 8-15 times faster than seen in the last 60 million years (Zeebe et al. 2009), we can expect further significant shoaling in the years to come. Under the IS92a scenario, it is predicted that atmospheric CO_2 will reach 780 ppm by the end of the 21st century, with values ~2,000 ppm being reached by the year 2300 (Caldeira and Wickett 2003). These pCO_2 increases equate to pH drops of 0.3-0.5 by the end of the century, a rate of change not seen in over 20 million years (Feely et al. 2004).

In the years since these predictions, studies have begun to examine the vulnerability of cold-water corals to ocean acidification. As with all deep-water organisms, progress has been limited by the difficulties and expense of sampling and maintaining these corals in laboratory experiments. As a result, we know far less about the response of cold-water corals to ocean acidification than we do about shallow-water species.

The studies carried out so far have focused on those cold-water corals that engineer habitat, primarily the reef framework-forming scleractinian corals. In 2009, Maier and colleagues presented the first information on calcification rates in *Lophelia pertusa* and showed that, over short incubations of 24 hours, reducing pH by 0.15 to 0.3 units caused a reduction in calcification of between 30 and 56%, but *L. pertusa* still maintained the ability to calcify at aragonite saturation states <1. Later work has provided more evidence that this species has some capacity to maintain calcification rates in reduced saturation states. Form and Riebesell (2011) maintained *L. pertusa* for six months in seawater with CO_2 concentrations of up to ~1,000 ppm and found evidence that the corals acclimated to these acidified conditions. Work is now developing to study the metabolic implications of any acclimation response. While no complete carbon and energy budgets yet exist there is emerging evidence that *L. pertusa* shows significantly lowered rates of respiration but unchanged calcification rates after 21 days exposure to elevated pCO$_2$ (750 ppm). This implies the corals are facing an energetic imbalance, forcing them to maintain calcification rates by using stored energy reserves (Hennige et al. 2014). However, none of these studies has examined the combined effects of ocean acidification and temperature increase. Evidence is now emerging that only when these two factors are combined, as they are in nature, do the real effects of ocean change become apparent.

Future Perspectives

It is clear that our understanding of the vulnerability of cold-water corals to global warming and ocean acidification is fundamentally limited by the lack of studies that have combined these two factors. At the time of writing, work was underway to address this major gap and results can be anticipated in the next 5-10 years. The response of these organisms to other perturbations, such as reduced oxygen levels and sub-lethal impacts of bottom trawling and sediment exposure, remain poorly understood. As with the need for combined studies of ocean acidification and temperature, we need integrated 'multi-stressor' experiments powerful enough to probe for critical points where synergies between these stressors may cause significant phase shifts in ecosystems functioning. It is also important to note that, so far, the response variables assessed are largely restricted to coral growth with a few studies that examine metabolic response via respiration rate measurements. We need to develop wider studies examining the effects of ocean acidification and warming upon other vital functions, notably reproduction but also organism behaviour and feeding rate.

Similar efforts are needed to build the scientific community's ability to monitor carbonate chemistry, temperature and key hydrographic parameters at a range of cold-water coral sites around the world. There is emerging evidence that the pH environment of these ecosystems may be far more variable than previously assumed (Findlay et al. 2013), but no opportunities currently exist for the long-term *in situ* monitoring of this variability into the future.

Europe is uniquely well-placed in terms of its scientific infrastructure and access to Atlantic margin ecosystems to contribute to the greater understanding of these issues. Without a sound scientific understanding of the impacts of global change on cold-water coral ecosystem function, efforts to ensure the long-term management and conservation of these vulnerable marine ecosystems will be impossible.

The take-home message

Across all coral taxa more species are found in waters over 50 m deep than live on shallow tropical coral reefs. Amongst these deep, cold-water corals there are six reef framework-forming scleractinian species. These create structurally complex deep-water habitats that are oases of rich biodiversity. However, as with all marine calcifiers, cold-water corals are threatened by the progressive acidification of the oceans brought about by the dissolution of anthropogenic carbon dioxide.

It is now recognised that approximately a third of the carbon dioxide released since the Industrial Revolution has dissolved in the oceans where it forms carbonic acid causing seawater pH to decline. Research into the impacts of ocean acidification on cold-water corals is at a very early stage, but the few studies available indicate that it is important to use long-term experiments and vital to include the effects of temperature increase alongside acidification. Future research will need to explore further synergistic effects of multiple stressors, expand to include permanent at-sea monitoring of carbonate chemistry and consider the implications for wider ecosystem function.

Companion reading

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Stresses on polar marine ecosystems: impact on key ecosystem functions and services

Cinzia Verde and Guido di Prisco – Melody S. Clark and Lloyd S. Peck – Federico M. Lauro

Statement

Marine ecosystems are among the most important systems used heavily worldwide in providing ecosystem services, including food from fisheries and aquaculture (Millennium Ecosystem Assessment 2005). The knowledge of how climate change affects marine ecosystems is trailing behind that of terrestrial ecosystems because of the complex nature of the marine world and the inherent difficulty with performing accurate measurements in these environments. Consequently, the literature that reports changes within marine ecosystems accounts for only 5% of the total number of publications (Hoegh-Guldberg and Bruno 2010).

In marine ecosystems, the rise of atmospheric CO_2 and climate changes are associated with shifts in temperature, pH, circulation, changes in the sea ice extent, stratification, oxygen content – with potential biological effects impacting the overall function of the ecosystem – and services. In recent decades, the rate of change has been very rapid, thus exceeding the potential capacity for species to adapt. The effects of climate change may start at the molecular/cellular level, triggering changes all the way to the organism/population levels. Finally, impacts on the population and community level may produce ecosystem-wide changes often unpredictable in thresholds and non-linear dynamics. The rates of potential biological responses vary in the range from hours/days to millions of years (Figure 3.10).

Therefore, given the cumulative effects of climate change and the risks for valuable ecosystem functions, there is urgent need for predictive studies and

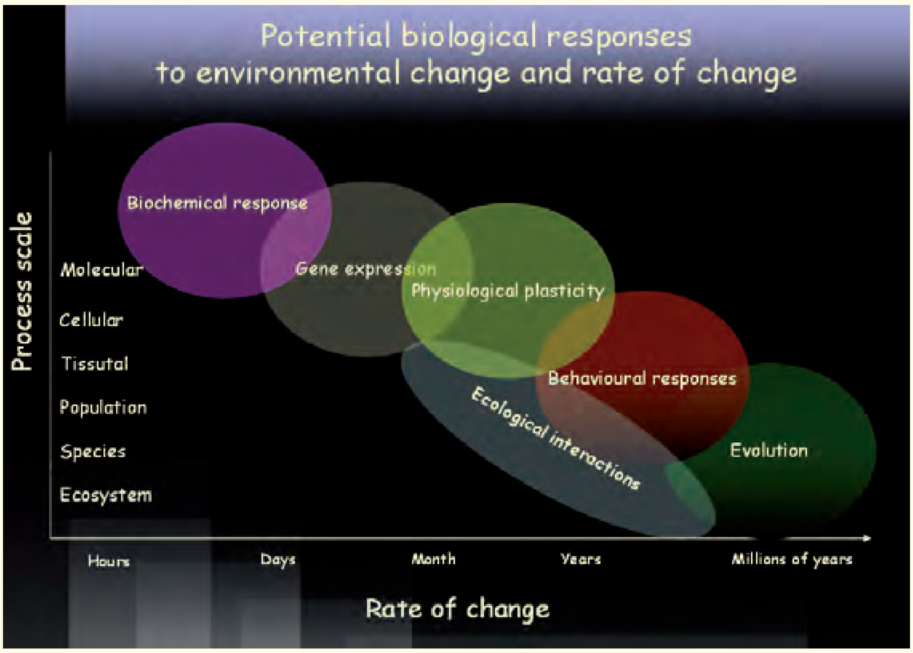

Figure 3.10. Potential biological responses to environmental change and rate of change. In a short-time range, a challenge may be met by homeostatic response. In a medium-time range, the response is mediated by the individual phenotypic plasticity. When the latter is exceeded, natural selection works on the population as a whole, and evolution occurs. Physiological plasticity will give advantages over several generations at the individual level. The responses of organisms vary across process scales, from the molecular to the ecosystem. Other responses, such as migration and ecological interactions, run across these scales.

management, integrating the multiple scales of biological organisation and function (Hoegh-Guldberg and Bruno 2010, Bernhardt and Leslie 2013).

Current Knowledge

The Polar regions have the lowest and most stable temperatures (Figure 3.11). The temperate regions, with most human inhabitation, are the most variable.

In both Arctic and Antarctic marine ecosystems, microorganisms dominate the gene pool and the biomass. They are integral to biogeochemical cycling and in the maintenance of proper ecosystem function. However, their resilience to environmental change and how this will translate to higher trophic levels is still poorly understood (Wilkins et al. 2012).

A recent review (Wassmann et al. 2011) documented changes in both biotic and abiotic interactions as a response of the Arctic ecosystem to climate change, including marine-species-range shifts, changes in behaviour, abundance and growth. In the Antarctic marine environments, there is a combination of globally lowest and most stable temperatures, with the highest oxygen content and greater variability in other variables, e.g., light, ice cover, phytoplankton productivity (Peck at al. 2006). The marine fauna is incredibly biodiverse, with many species displaying unique adaptations (such as gigantism in invertebrates, giant muscle fibres and reduction in number in fish, deletion of haemoglobin genes and lack of a heat-shock response) that allow them to live in such a permanently cold environment. In addition, the fauna is generally characterised by slow growth and metabolic rates, slow development, deferred reproductive maturity and long life spans. These species are also amongst the most stenothermal on the planet, most being unable to survive for extended periods of time (months), above 2-3°C (Somero 2012).

Sea temperatures around this continent have remained stable for many millions of years and even in the shallow waters of the Antarctic Peninsula, which is acknowledged as the most variable region, temperatures rarely reach above 0°C for extended periods of time. However, the Peninsula is also one of the regions in the planet that is warming fastest, both on land and in the sea. This is clearly an area for concern. Similar to the Arctic, warming has especially significant impacts on cold- and ice-adapted species as their suitable habitats contract. Both the IPCC (2007) and the Millennium Ecosystem Assessment (2005) emphasise the need to predict the impact of climate change on our planet and on the inherent biodiversity that shapes our world. Hence, there is a pressing need to understand the stresses on the Arctic and Antarctic organisms and, specifically, to predict how organisms respond and how these refrigerated marine ecosystems will change *vis-à-vis* climate-change events. This will place us in a better position to evaluate resilience (the capacity of a system to maintain functioning, structure and feedbacks when disturbances occur) and vulnerability of the endemic faunas, requiring a detailed understanding of the underlying mechanisms of the adaptations, in particular how they feed into larger-scale processes to enable us to make ecosystem-level predictions (Figure 3.12).

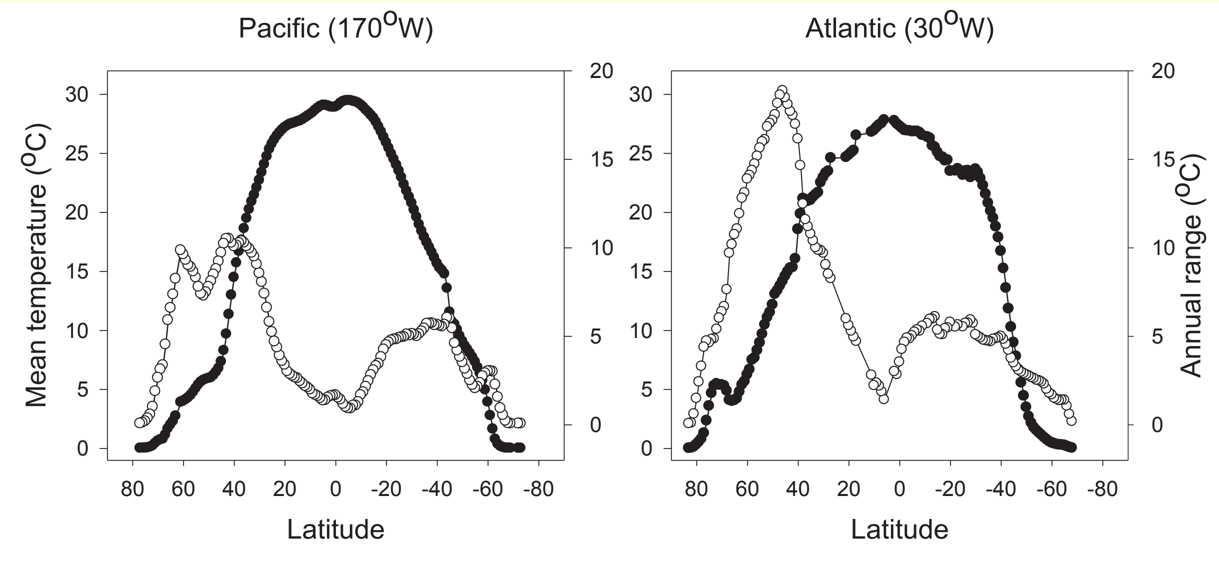

Figure 3.11. Mean annual temperature (filled circles) and annual range (maximum–minimum experienced temperatures, empty circles) for transects through the Pacific and Atlantic oceans from the high Arctic to Antarctica. Modified from Clarke and Gaston (2006).

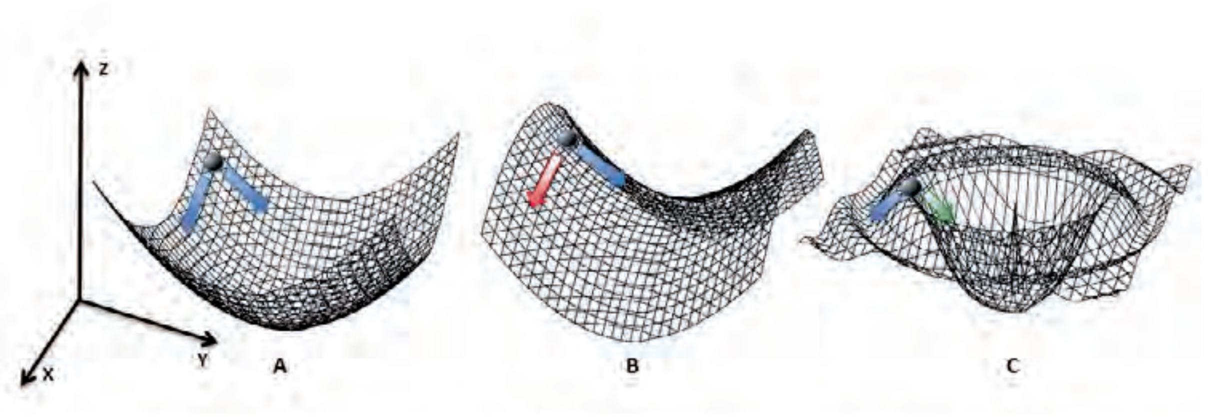

Figure 3.12. Graphical description of three possible outcomes of environmental perturbations on a system (e.g., individual cell, community, ecosystem) highlighting the relevance of resilience and tipping points. On the X and Y axes are two hypothetical environmental properties, on the Z axis the system state. The location of the system is represented by a ball and is constrained by a surface of possible states. In (a) the system is highly resilient and, after any movement from the equilibrium point as a result of perturbation on one or more environmental axes, the system tends to return to its initial state. In (b) the system is resilient along one environmental axis but very close to its tipping point along the other. Any slight movement from the equilibrium will cause it to drastically change into an alternative state (red arrow). In (c) the system can fall into either alternative stable state. One state (green arrow) is much more resilient than the other.

Understanding how systems respond to environmental perturbations is a key to management and conservation. This will require the development of new integrative approaches for establishing and supporting resilience in target systems (Scheffer et al. 2001). The adaptive capacity of species and ecosystems is an essential component of resilience and it includes organism plasticity, species range shifts, and genetic adaptation through evolution of some characters better suited to new conditions, if the evolutionary potential exists. Antarctic marine organisms adapted to stable conditions could not keep up with the rates of current climate changes (Peck 2011, Somero 2012), whereas Arctic organisms, exposed to less stable regimes, would have larger flexibility and respond differently. For instance, species distribution may be affected, with southern species moving north as the ocean gets warmer, thus joining high-Arctic species.

Future Perspectives

As a consequence of the stresses brought about by climate change (including extreme events) and human impacts, polar ecosystems are changing. A cascade of responses, from molecular through to wide-scale organismal at the community level, are expected as a result of these stresses during ongoing changes. Currently, the climate of the poles is changing faster than anywhere on Earth and then the poles may serve as both a bellwether of climate changes and an example of the changes that we can expect elsewhere. The differences in biological complexity and evolutionary histories between the Polar regions and the rest of the planet suggest that stresses on polar ecosystem function may have fundamentally different outcomes than those at lower latitudes. Polar ecosystem processes are therefore key to informing wider ecological debate about the nature of stability and potential changes across the biosphere. In the Antarctic, 17-20,000 species are predicted to live on the continental shelf, 80% of which are yet undescribed. Observations of ecosystem changes reveal that the new ecosystems have arisen because of ice shelf and glacier retreat. In addition, changes in krill distributions occur along with changes in sea-ice cover. Together with changes in current regimes, formation of deep water is slowing, and the consequences are uncertain. The Peninsula is warming fast, but the rest of the continent is cold, most likely because the ozone hole is keeping it cold. If and when the ozone hole closes, Antarctica will warm fast. Antarctic marine organisms are highly stenothermal, physiological rates are slow, and in addition some of the adaptations are irreversible, e.g., haemoglobin deletions and mutation in promoter region of the inducible heat-shock proteins. Consequently, fast warming is likely to impact heavily on a number of marine species.

Because of the difficulties in performing measurements, the adaptive genetic diversity is not yet considered a priority in conservation management. However, the recent advances in genome sequencing can help the detection of genomic regions under selection by large geographic-scale projects. In great part due to large-scale oceanographic expeditions such as the Global Ocean Sampling (Nealson and Venter 2007) and Tara Oceans (Karsenti 2012), the number and extent of environmental sequencing projects has increased dramatically in the past 10 years. The integration of this wealth of data with functional studies (e.g., metaproteomic, metatranscriptomic) has the potential to revolutionise our understanding of the structure-function of polar ecosystems as a whole.

The complexity of the questions and their implications in the impact of global changes on the whole planet call for several approaches, some of which are closely interconnected. In collaboration with climatologists, identification of the rates of change will help long-term predictions of resilience/sensitivity to exploitation and environmental change. Relying on the rapid development of genomic technologies, it will be possible to do fine-scale population analyses and functional studies, thus combining physiology and genomics. We need to investigate a high number of species to get ecosystem-level evaluations; from this we need to understand variability across scales from genes to ecosystems. Further important research targets include (i) physiology-to-ecosystems linkages and the development of models, (ii) sampling strategies and analytical methods to understand the interplay between microbes and viruses and the role of the 'microbial-loop' in the function of polar ecosystems, (iii) effect of gene flow on reproduction and life histories, (iv) links to currents, seasonal resource availability and specifically polar factors, e.g., iceberg scour, (v) the importance of biogeography and dispersal linked to changes in oceanic circulation, (vi) identifying other deletion-type adaptations. We need to reach deeper knowledge of the concept of microbial 'species' and how this affects microbial conservation at the level of individual ecotypes and functional communities. Fishing will provide suitable experimental material (krill, fish, squid, crabs).

Research will address:

- Habitats in Arctic and Antarctic Oceans, including connectivity, gene flow and its change under current environmental change
- Local and regional biodiversity, from microorganisms to vertebrates; impacts of biodiversity change on ecosystem function and services
- Combination of cutting-edge bottom-up and top-down approaches *in situ*, in the laboratory (e.g., 'omics') and *in silico* (e.g., modelling and database mining)
- Time-series observations of key biological processes at different trophic levels
- Investigations on key pelagic/benthic species to evaluate response to ocean acidification
- New molecular information, to establish (a) trade-offs and costs of adaptation, (b) rates of evolution vs environmental change, (c) consequences of adaptation to cyclic versus directional change, (d) interaction of selective pressures (evolutionary and ecological processes) in promoting or hindering adaptation, and (e) impacts of climate change on key ecosystem functions and services.

At a higher level of detail, the main research objectives are:

1. To define and facilitate the science required to examine changes in biological processes, from the molecular to the ecosystem level, in polar marine ecosystems.
2. To determine tolerance limits, as well as thresholds, resistance and resilience to environmental change.
3. To promote physiological analyses at the whole-organism level in order to identify aspects of stress caused by environmental changes. These studies will be helpful to ecologists and biological oceanographers for developing biological models based on biogeography, as well as species distribution patterns.
4. To promote transcriptomic and proteomic analysis on model organisms (e.g., ectotherms living in the thermally stable waters of the Southern Ocean), in order to facilitate the development of suitable biomarkers for gauging stress exposure under field conditions. These studies may allow prediction of the different capacity of species to cope with global change.
5. To develop methods for the integration of functional, physiological and genomic data within the framework of the chemico-physical environment. These methods will facilitate future *in silico* modelling to predict evolutionary patterns of individual genomes and communities in response to climate changes.
6. To understand how human activities and climate changes are likely to interact in affecting the delivery of ecosystem services. In this context, this may be viewed as an ecosystem service itself (i.e., a form of ecological insurance).
7. To establish and expand multidisciplinary and interdisciplinary efforts, in conjunction with earth and physical sciences and oceanography (Gutt et al. 2013), in the framework of large international institutions and programmes (e.g., SCAR: EBA, AntEco, AnT-ERA, SOOS, etc).

The take-home message

Climate in the Polar regions is rapidly changing with substantial effects on organism physiology, populations of individual species, and community composition and biodiversity. In this context, non-linear responses, thresholds and counter-intuitive effects may arise. The current state of knowledge highlights the need for a more comprehensive, multispecies approach to ecosystem-level analyses. Research needs (i) cutting-edge bottom-up and top-down approaches *in situ*, in the laboratory and *in silico*; (ii) historical data synthesis; (iii) long-term, biologically oriented observational systems at different trophic levels; (iv) measurements of *(a)* trade-offs and costs of adaptation, *(b)* rates of evolution *vs* environmental change, *(c)* consequences of adaptation to cyclic versus directional change, *(d)* interaction of selective pressures in promoting or hindering adaptation, *(e)* impacts of climate change on key ecosystem functions and services; (v) Arctic *vs* Antarctic comparisons.
Studying the impact of stresses on key ecosystem functions and services of polar marine ecosystems is based on searching for answers to many key questions, such as, for example:

- How are polar organisms adapted to current and future environmental conditions and what is the genetic basis for their life history, organism plasticity and physiology?
- In parallel, at the functional level, which drivers have had a role in polar evolution and what was gained and lost over millions of years in response to these drivers?
- What role will adaptation play in modulating the rate of climate-driven marine ecosystem change?
- What capacities do Antarctic species have to adapt *via* mutation and gene flow, and do they have the physiological flexibility to allow these processes to become entrained?
- What are the underlying mechanisms behind species resilience/sensitivity to environmental change?
- How much do specific adaptations make polar species less resilient to change than faunas elsewhere?
- How does environmental change affect population performance and species interactions?
- What are the likely consequences of a changing environment for key ecosystem functions and services?
- How can we feed our genetic, genomic, biochemical and physiological data into ecosystem-scale models to allow ecologically relevant predictions of functional relationships and effects on ecosystem services?
- How do ecosystem tipping points scale across processes, from molecular to community levels?

Companion reading

AntEco: State of the Antarctic Ecosystem, www.scar.org

AnT-ERA: Antarctic Thresholds – Ecosystem Resilience and Adaptation, www.scar.org

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EBA: Evolution and Biodiversity in the Antarctic – The Response of Life to Change, www.eba.aq

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SCAR: Scientific Committee on Antarctic Research, www.scar.org

SOOS: Southern Ocean Observing System, www.soos.aq

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Chapter 4

Ocean and Polar Life and Environmental Sciences in Horizon 2020: opportunities and needs

Paola Campus – Roberto Azzolini

Horizon 2020: Background in Marine and Polar Science Priorities

The period of preparation of this manuscript witnessed a significant change in the European research scenario, characterised by the transition phase from the European Commission's 7th Framework Programme (FP7) to the new EU Framework Programme for Research and Innovation, Horizon 2020.

Following the announcement of the forthcoming conclusion of FP7 and of the planned new structure of Horizon 2020, based on the three main pillars 'Excellent Science', 'Competitive Industries' and 'Tackling Societal Challenges', all the scientific European clusters focused on identifying the existing gaps in knowledge and top priorities for their research in the time window 2014-2020. In this preparatory phase, several such clusters expressed concerns for finding an appropriate niche for their research in the forthcoming calls of Horizon 2020, based on the up-to-date information emerging from the Commission's dissemination actions.

For a number of marine and polar topics linked to climate change, life and environment, several publications were produced between 2011 and 2014 by scientific clusters and international organisations: some of those publications specifically aimed at influencing the forthcoming Horizon 2020 calls, while some others (in particular those linked to international organisations) used a more general approach to highlight the main societal needs for achieving sustainable development, respectful of the environment.

The topics covered by these publications refer to phenomena on a global scale, often including polar areas; sea level rise, changes in marine ecosystems, climate change and ocean acidification are affecting the whole planet, including Polar regions. However, some specific phenomena (e.g., permafrost, ice melting, recent climate change and adaptation of marine organisms) are more closely related to polar areas. Taking into account the publications of the major scientific clusters and international organisations, a summary highlighting the principal conclusions and recommendations addressing climate change and life and environmental issues is herewith provided both for global scale and for specific phenomena occurring at polar scale.

Such a summary will serve as the basis to analyse how many of the principal conclusions and recommendations in the domain of marine and polar science linked to climate change, life and environment have been already addressed by the first Work Programme 2014-2015 of Horizon 2020 and related calls. The analysis will further develop by highlighting which scientific priorities in the same domain are still in need of finding a niche in the second and third run of calls of the forthcoming Horizon 2020 work programmes.

Climate Change & European Marine Ecosystem Research (CLAMER)

Climate Change & European Marine Ecosystem Research (CLAMER), funded under FP7, produced 'The CLAMER Booklet' (Reid, P.C., Gorick, G. and Edwards, M. 2011, http://www.clamer.eu/outreach/booklet), which addressed a number of key issues in the scientific domain of global change and its impact on the marine environment. The manuscript specifically addressed the following scientific challenges: changes to temperature, the thermohaline circulation and ice; sea level, coastal erosion and storms; microorganisms and the microbial loop; ocean acidification; marine eutrophication and coastal hypoxia; shifts in species composition and biodiversity; non-native species; fisheries and aquaculture. Among the key issues highlighted by the publication, the Arctic areas cover a special role, since major consequences for the weather, water cycle and socioeconomics of Europe and the Arctic should be expected as a consequence of sea-level rise. In this context, the following major research areas in urgent need of further development have been highlighted:

- Ocean/atmosphere interactions and processes during the current rapid warming
- Factors that contribute to spatial variability of sea-level rise
- Response to global warming: implications for carbon sequestration and fish-carrying capacity
- Critical microbial processes contributing to biogeochemical cycling and microbial diversity
- Response to ocean acidification: benthic and pelagic biota, biogeochemical cycles, links with global warming, sea ice and freshwater runoff in Polar regions
- Linkages between eutrophication symptoms and nutrients and effects on living marine resources and health of ecosystems
- Warming sea temperature impact on biogeochemical cycles, living marine resources, ecosystem resilience and human health
- Functioning of ocean ecosystems as potential platform to apply new technologies and reduce the rising of atmospheric CO_2.

The EC Marine Strategy Framework Directive (MSFD, 2008/56/EC)

The EC Marine Strategy Framework Directive (MSFD, 2008/56/EC), adopted in June 2008, developed parallel actions to CLAMER and devoted a special focus to marine environment and biodiversity.

The MFSD calls for the development of a marine strategy by each Member State, aimed at the following targets:

- To gather, by 2012, a comprehensive assessment of the state of the environment, identifying the main pressures on its respective marine regions and defining targets and monitoring indicators;
- To develop coherent and coordinated programmes of measures by 2015 through the establishment of regional sea conventions, efficient communication and close cooperation;
- To achieve Good Environmental Status (GES) of its national marine waters by 2020.

The MFSD highlights the importance of using an ecosystem-based approach for the marine environment and requests the Member States to take into consideration in their assessments various climate-related factors, such as:

- Changes in sea temperature and ice cover
- Ocean acidification
- Impact deriving from a potential use of marine areas for the generation of renewable energy
- Carbon capture and storage (CCS).

The Marine Strategy Framework Directive is the first EU legislative instrument explicitly related to the protection of marine biodiversity in its entirety and aiming to maintain the biodiversity by 2020: it provides a key contribution to the obligations specified by the United Nations Convention on the Law of the Sea (UNCLOS) and the establishment of Marine Protected Areas (MPAs).

In addition, being concerned with a deeper understanding of the impacts of climate change on the marine environment, the Marine Strategy Framework Directive contributes indirectly to the UN Framework Convention on Climate Change (UNFCC).

In summary, the MFSD establishes a strong link between the top priority scientific issues in marine biodiversity and Policy Makers.

The EU publication *Seas for Life* (2011, ISBN 978-92-79-18550-2, doi:10.2779/18719) provides a very useful overview of the mission and main targets of the EC Marine Strategy Framework Directive and concurs with the CLAMER Report in identifying a number of key research priorities in biodiversity and climate-related factors which need to be developed in the coming years.

Joint Programming Initiative Healthy and Productive Seas and Oceans (JPI Oceans)

The Joint Programming Initiative on Healthy and Productive Seas and Oceans (JPI Oceans) has been put in place by the EU Member States (MS) and Associated Countries (AC) to solve the main challenges related to seas and oceans in Europe using a coordinated approach.

JPI Oceans has contributed to the work already conducted by various organisations, initiatives and projects at the European level (notably SEAS-ERA, BONUS, EUROMARINE, CLAMER, the European Marine Board, EFARO and ICES) to map the activities, gaps and needs at EU level in marine and maritime research.

The publication of JPI Oceans entitled *JPI Healthy and Productive Seas and Oceans. Input Horizon 2020*, available under http://www.jpi-oceans.eu/library and published in 2013, aimed to provide inputs to Horizon 2020, highlighting the existing need to develop long-term programmatic and strategic areas at the intersection between climate, the marine environment and the blue economy. The document stresses the importance of understanding the functioning of marine and coastal ecosystems and their interactions with climate and human activities: only through such understanding will it be possible to respond to changes and threats to seas, oceans and coastal areas.

A number of key questions addressing three main topics – climate changing the ocean, healthy oceans, seas and coasts, and a sustainable blue economy – were proposed in the document, followed by a gap analysis study, highlighting the research areas in need of further development at the intersection between climate, marine environment and the blue economy, the three target areas of JPI Oceans. Of particular relevance for ocean and polar life and environment on a warming planet are the following research areas, which find numerous correspondences with the priorities of the *Seas for Life* publication:

- Role of the ocean in the past as climate regulator and the impact of climate change on the ocean circulation patterns, water masses formation and water exchanges, including related feedbacks;
- Impact of climate change on biodiversity (including exploitation and invasive species), on the functioning of marine ecosystems and the related value of ecosystem goods and services, including effects on human health;
- Effects of climate change and ocean acidification on coastal and shallow marine ecosystems, on pelagic food webs dynamics, on biogeochemical and geochemical processes, on the status and functioning of benthic marine ecosystems (including deep sea), on the ecology, distribution and population dynamics in marine ecosystems;
- Development of sensors, systems, observatories, methods and models to observe and predict the climate and its changes at different scales; to monitor and assess the status of the marine environment, including pollution; to predict the ecosystems and biodiversity evolutions in response to climate and anthropogenic changes;
- Understanding and quantification of the effects of climate change and melting of ice in the Arctic, including the assessment of opportunities and risks associated to the opening of the area;
- Identification of risks and impacts on the marine environment and ecosystems (including coastal areas and shelf processes) associated to sub-seabed carbon storage and sequestration, radioactive pollution, marine litter and pollution, oil and gas extraction (including gas hydrates), deep sea mining, noise, geohazards, wind farms and ocean energy, fishing, aquaculture;
- Development of indicators of the Good Environmental Status (GES) to provide support to the implementation of the EC Marine Strategy Framework Directive.

The JPI Oceans document also underlines the importance of generating stronger synergies among marine scientists through a number of infrastructures, common databases, networks and observatories to share and access marine data, emphasising in particular the development of the European Marine Observation Data Network.

Another key message the JPI document has conveyed is the development of knowledge and tools by the scientific experts both to support the policy and decision makers in their understanding of the main scientific issues and to build capacity in the new generations of scientists.

The main concepts and priorities identified in *JPI Healthy and Productive Seas and Oceans. Input Horizon 2020* (2013) are essentially reiterated by JPI Oceans in the new document *Needs and gaps analysis in marine sciences to feed the SRIA*, available under http://www.jpi-oceans.eu/library and published in 2014. The Work Package 3 (WP3) of the Coordination and Support Action (CSA) of JPI

Oceans described in the publication focuses on a survey carried out to identify specific cross-cutting needs and gaps in two scientific areas targeted by JPI Oceans: marine environment-climate change and maritime economy-climate change.

The consultation with research funding agencies and stakeholders has been focused on two goals of JPI Oceans: ensure good environmental status of the seas and optimise planning of activities in the marine space; and optimise the response to climate change and mitigate human impacts on the marine environment.

The analysis of the scientific priorities identified by the CSA-JPI Oceans WP3 shows a strong similarity with the main themes and priorities identified by relevant pan-European and regional marine science organisations and initiatives (European Marine Board, EFARO, EUROMARINE, ICES, CIESM, SEAS-ERA, BONUS Article 185 and CLAMER). This confirms the importance of such priorities in the European landscape and reiterates the need for aligning the national research agendas with the European scenario.

European Marine Board: Navigating the Future IV

The twentieth Position Paper of the European Marine Board (EMB), *Navigating the Future IV* (NFIV, Marine Board Position Paper 20), published in mid-2013, aimed at influencing the development of the Horizon 2020 work programmes by identifying the most important research challenges and priorities in marine environments in the next 5-10 years.

Through an analysis of the state-of-the-art of all the main ongoing or completed European programmes and consortia dealing with marine and maritime science and policy, the position paper addresses under Chapters 2, 3 and 9 the following main challenges:

- Understanding the marine ecosystems and their societal benefits
- Changing oceans in a changing earth system
- Challenges in polar ocean science.

In Chapter 2 NFIV highlights the importance of reaching a deeper understanding of marine ecosystems and related services, of their current state, structure and functioning and of the mechanisms to assess and improve ecosystem health.

In Chapter 3 NFIV analyses the effects of climate on marine environments and related feedbacks.

In Chapter 9 NFIV projects the basic issues of Chapter 3 in the specific environment of the Polar regions, adding a specific concern for the increasing loads of Chromophoric Dissolved Organic Matter (CDOM) in the Arctic Ocean and for the potential increase of maritime transport in the Arctic regions.

The main research recommendations arising from these chapters reiterate the recommendations of previous EMB publications and basically concur in highlighting a significant number of priorities identified also by CLAMER and JPI Oceans.

The key areas linked to ocean and polar life and environment on a warming planet in need of further development and the associated main scientific topics are summarised in Table 4.1.

The United Nations Conference on Sustainable Development (UNCSD) Rio+20 and the theme of Oceans

The United Nations Conference on Sustainable Development (UNCSD) Rio+20 took place on 20-22 June 2012 and addressed the issues of reducing poverty, advancing in social equity and ensuring environmental protection on a more and more populated planet.

The RIO +20 Report highlights a number of priority issues related to marine environments.

The first reference to marine environments can be found under point 113 of 'Chapter V. Framework for action and follow-up', area 'Food security and nutrition and sustainable agriculture', where the Report stresses the crucial role of healthy marine ecosystems, sustainable fisheries and sustainable aquaculture to assure food security and nutrition.

A larger reference to marine environments and related social issues can be found under the area 'Oceans and seas' (points 159 to 177), where the Report highlights:

- The importance of the United Nations Convention on the Law of the Sea (UNCLOS) to make progress in sustainable development.
- The importance of capacity building in developing Countries: through this process developing Countries would benefit from the conservation and sustainable use of the oceans and seas and their resources.
- The need for cooperation in marine scientific research to implement the provisions of the United Nations Convention on the Law of the Sea (UNCLOS).
- The need for technology transfer based on the Intergovernmental Oceanographic Commission Criteria and Guidelines on the Transfer of Marine

Table 4.1. Summary of key areas and scientific priorities in need of further development and linked to ocean and polar life and environment on a warming planet in the EMB publication *Navigating the Future IV*.

Theme	Topics
Biodiversity and ecosystems	• Discovery, description and characterisation of marine biodiversity • Human benefits deriving from seas and oceans; human and natural threats to seas and oceans • Adaptation of species and populations to changing marine environments • Controls and limits of ecosystem resilience • Definition of ecosystem health to contribute to the GES target of the EU Marine Strategy Framework Directive
Sea-level changes	• Progress in understanding ice sheet break-up processes and integration of ice sheet modelling into global climate models • Progress in understanding coastal sea-level forcing mechanisms and integration in climate models to account for regional variability • Development of a robust and efficient monitoring system for mass changes in Greenland and Antarctica • Forecasting regional / local sea-level rise
Coastal erosion	• Study of relative sea-level trends in relation to future storm tracks • Detailed assessment of the extent of coastal erosion in the EU at appropriate temporal and spatial scales • Progress in societal understanding of coastal erosion and of the difference between coastal protection and protection of the coastal ecosystem
Temperature and salinity changes	• Improvement in detection capability of long-term temperature and salinity changes with special focus on deep layers • Identification and reduction of uncertainty for sea surface temperature (SST) and sea ice in climate modelling systems • Increase of the resolution of coupled regional atmosphere – ocean circulation models • Improvement of parameterisation of dominant processes for accurate SST simulation in coupled climate models (at global and regional scales, past and present) • Study of patterns of climate change of the northern hemisphere influencing Mediterranean water temperature and salinity changes
Ice melting	• Progress in understanding properties of snow cover on sea ice • Progress in assimilation of observation data in forward models of the Arctic sea-ice cover (special focus on relation between ice physical parameters and electromagnetic properties) • Progress in understanding and quantification of the interaction ocean – ice melt
Storm frequency and intensity	• Progress in understanding properties of snow cover on sea ice • Progress in assimilation of observation data in forward models of the Arctic sea-ice cover (special focus on relation between ice physical parameters and electromagnetic properties) • Progress in understanding and quantification of the interaction ocean – ice melt
Changing stratification	• Boundary conditions for increasing atmospheric supply of nutrients and oceanic vertical supply • Progress in prediction of effects of altered productivity throughout marine ecosystems • Inclusion of effects of altered stratification on other ocean properties
Thermohaline circulation (THC) changes	• Key factors determining thermohaline circulation changes and global warming impact on freshwater input to the North Atlantic • Accuracy of current climate models to predict the THC system and impact of THC predictions on improvement of climate forecasts • Global warming impact on freshwater input to the North Atlantic and corresponding impacts on Mediterranean Sea • Relationship between intensity of Mediterranean overturning circulation and deep mixing rates
Riverine discharge and nutrient loads	• Interactive effects of floods, global temperature increases and coastal biogeochemistry (past and present) • Coupling regional climate change scenarios with river basin, nutrient transfer and coastal ecosystem models • Better understanding of possible responses of coastal ecosystems to changing riverine nutrient loads
Ocean acidification	• Significant improvement in understanding the impacts of ocean acidification on marine taxa and underlying processes (past and present) • Monitoring of acclimation and adaptation (individual organism and community) • Synergy between simultaneous changes of temperature, oxygen and pH • Improvement of representation of biological responses to climate change and ocean acidification (regional and global models) • Distributions, controls and temporal variability of natural and anthropogenic carbon in the interior of the sea (key areas for CO_2 sequestration, role of water formation areas, role of shelf events) • Creation of a Mediterranean–Black Sea component of the Global Ocean Ship-based Hydrographic Investigations Programme (GO-SHIP), to improve understanding of carbon fluxes and processes

Theme	Topics
Ocean deoxygenation and coastal hypoxia	• Spatial and temporal dynamics of oxygen in both open ocean and coastal environments (past and present) • Drivers of oxygen depletion and identification of natural variability and anthropogenic impacts • Establishment of a global observation system for oxygen concentrations at high resolutions, linked to physical, biogeochemical parameters and climate observations • Processes of formation of dead zones resulting from oxygen depletion • Improvement of existing models to better predict frequency, intensity and duration of future hypoxia events
Impacts of climate change on marine eutrophication	• Increase of consistent measurements of pelagic primary production • Address lack of data on benthic primary production in shallow seas • Improve knowledge to differentiate between factors affecting simultaneously growth and loss of microalgae • Progress in understanding impacts of nutrient load on primary production; identification and quantification of trophic transfers between primary and secondary producers
Biological impacts	• Study of links biodiversity-ecosystem modelling and ecology-biogeochemistry for improving prediction and risk analysis of climate change impacts on biological communities and ecosystems (past and present) • Application of individual based models (IBMs) in climate change predictions • Improvement of knowledge on ability of marine organisms to adapt and evolve to climate change on relevant timescales • Drastic improvement in understanding of impacts of fishing on the abilities of marine populations and ecosystems to respond to climate change • Systematic and sustained observation on long-term and large-scale changes in distribution of key organisms and biodiversity

Technology.

- The importance of assessing the state of the marine environment by 2014.
- The importance of assuring conservation and sustainable use of marine biodiversity beyond areas of national jurisdiction.
- The concern that the health of oceans and marine biodiversity are negatively affected by marine pollution, including marine debris, especially plastic, persistent organic pollutants, heavy metals and nitrogen-based compounds, from a number of marine and land-based sources, including shipping and land run-off. The commitment to take action to reduce the incidence and impacts of such pollution on marine ecosystems is clearly expressed along with the commitment to take action, by 2025, based on collected scientific data, to achieve significant reductions in marine debris to prevent harm to the coastal and marine environment.
- The significant threat that alien invasive species pose to marine ecosystems and resources and the consequent need for implementing measures to prevent the introduction of alien invasive species and manage their adverse environmental impacts.
- The serious threat of sea-level rise and coastal erosion for many coastal regions and islands, particularly in developing Countries.
- The call for support to initiatives that address ocean acidification and the impacts of climate change on marine and coastal ecosystems and resources.
- The need to work collectively to prevent further ocean acidification, as well as enhance the resilience of marine ecosystems and of the communities whose livelihoods depend on them, and to support marine scientific research, monitoring and observation of ocean acidification and particularly vulnerable ecosystems.
- The concern for the potential environmental impacts deriving from ocean fertilisation.
- The commitment to urgently develop and implement science-based management plans, to maintain or restore stocks (target 2015) and to enhance actions to protect vulnerable marine ecosystems from significant adverse impacts.
- The need for transparency and accountability in fisheries management.
- The significant economic, social and environmental contributions of coral reefs, in particular to islands and other coastal states, as well as the significant vulnerability of coral reefs and mangroves to impacts, including climate change, ocean acidification, overfishing, destructive fishing practices and pollution.
- The importance of implementing area-based conservation measures, including marine protected areas, consistent with international law and based on best available scientific information. Such conservation measures should represent a tool for conservation of biological diversity and sustainable use of its components.
- The decision made at the 10th Meeting of the Conference of the Parties to the Convention on Biological Diversity that 10% of coastal and marine

areas, with special focus on biodiversity and ecosystem services areas, are to be conserved by 2020 through effectively and equitably managed, ecologically representative and well-connected systems.

Under the area 'Climate Change', point 190, the Report reaffirms that climate change is one of the greatest challenges of our time, emphasising that adaptation to climate change represents an immediate and urgent global priority. The Report also expresses the concern that all Countries are vulnerable to the adverse impacts of climate change, and are already experiencing increased impacts, including persistent drought and extreme weather events, sea-level rise, coastal erosion and ocean acidification.

The Report addresses the following basic recommendations for the theme 'Oceans':

1. Avoid ocean pollution by plastics through education and community collaboration.
2. Launch a global agreement to save high seas marine biodiversity.
3. Take immediate action to develop a global network of international marine protected areas, while fostering ecosystem based fisheries management, with special consideration for small-scale fishing interests.

In summary, with its holistic approach addressing key societal issues in relation to the environment, the RIO+20 Report highlights the need for developing a deeper scientific understanding of marine environments in a changing planet, for establishing common platforms of observations and for reinforcing the dialogue between scientific experts and policy makers.

The contribution of the International Atomic Energy Agency (IAEA) to the monitoring and protection of marine environments

The International Atomic Energy Agency (IAEA) recognised several decades ago the importance of protecting oceans, coastal areas and marine environments and developed a number of significant initiatives.

In 2011, the IAEA's Marine Environment Laboratories (IAEA-MEL) in Monaco celebrated their 50th anniversary. For decades the laboratories have been making radionuclides and stable isotopes available for the study of environmental processes, including the fate of contaminants in ecosystems, the atmosphere–ocean interactions, the surface and groundwater systems and the response of atmospheric, hydrological and marine systems to climate change.

The main tasks of IAEA-MEL are to:

- Conduct studies for the protection of the marine environment from radioactive and non-radioactive pollution;
- Develop applications of nuclear and isotopic techniques to increase the understanding of oceanic processes, marine ecosystems and pollution impacts;
- Provide expertise, training and reference materials to assist the IAEA member states' commitments to monitor marine environments and promote their sustainable development;
- Establish and sustain strategic partnerships with the United Nations (UN) and their international agencies to deliver the World Summit on Sustainable Development (UN-WSSD) programmes on sustainable development of the oceans;
- Act as a networking centre for the IAEA member states, with an increasing focus on normative activities.

The 2013 IAEA Scientific Forum, entitled 'The Blue Planet — Nuclear Applications for a Sustainable Marine Environment' focused on the joint work of the IAEA and of its member states and international partners aiming to, first, monitor and evaluate the challenges facing the oceans and, next, seek solutions.

Through the contribution of the IAEA Marine Environment Laboratories in Monaco to the study of the sources of pollution and its dispersion using isotopes, the IAEA announced at Rio+20 in June 2012 the establishment of the Ocean Acidification International Coordination Centre (OA-ICC) at the IAEA Environment Laboratories in Monaco. The OA-ICC's mission is to facilitate global actions and responses to ocean acidification. Established initially for a three-year period as a project, the work of the OA-ICC is funded and supported by several IAEA member states through the IAEA's Peaceful Uses Initiative. OA-ICC cooperates with other major national and international projects involved in ocean acidification research, thus offering opportunities for synergies to several scientific clusters.

European Polar Science

Europe has an internationally acknowledged leadership in many key areas of polar research. This is coupled with a wide-ranging infrastructure and operational capabilities both in the Arctic and in Antarctica.

Over the last 10 years around 200 M€ of EU funds has been allocated to Arctic research through FP6 and FP7. An average of 20 M€ per year has been allocated for research aimed at furthering the understanding of natural processes affecting the Arctic, including climate change, contaminants and their impact on local populations and economic activity. It also supports strengthening research networks, infrastructures and environmental technologies (ref: The inventory of activities in the framework of developing a European Union Arctic Policy, 2012)

The European Polar Research Network represented by the European Polar Board includes 22 Antarctic stations + several, 28 Arctic stations, 13 research icebreakers and ice-class vessels and polar aircraft (ref: European Polar logistic stations Consortium – ERAnet, Final Report). In addition, two international scientific networks are managed by European institutions, the Svalbard Integrated Earth Observing System (SIOS) and the International Network for Terrestrial Research and Monitoring in the Arctic (INTERACT), which also integrates Arctic stations and observatories belonging to non-European Countries.

Arctic Region

The Arctic region, and particularly the European Arctic, is an area of growing strategic importance to the EU. The communication of the European Commission to the European Parliament n. 763, 2008: *European Union and the Arctic Region*, indicates the main reasons for European interest in the Arctic, which may be summarised as follows:

- Existence of strong historical, geographic, economic and scientific links between Europe and the Arctic.
- Some European and European-connected Countries have direct national interest in the Arctic. Denmark (including Greenland), Finland and Sweden are Arctic member states, Iceland and Norway are members of the European Economic Area, Canada, Russia and the United States are strategic partners.
- The Arctic is a vital and vulnerable component of the Earth's environment and climate system; Arctic changes are expected to have significant impacts on the life of European citizens for generations to come.
- New technologies are gradually opening access to Arctic living and non-living resources as well as to new navigation routes. Arctic regions will be increasingly at risk from the combined effects of climate change and increasing human activity.
- Environmental changes are altering the geostrategic dynamics of the Arctic, calling for the development of an EU Arctic policy.

From 2008 to 2014, the European Parliament, the European Commission and the Council of the European Union adopted several important resolutions on Arctic issues, among which:

- European Commission: Communications from the Commission to the European Parliament, COM 468 and COM 763: The European Union and the Arctic Region – 2008
- Council of the European Union: Council conclusions on Arctic issues – 8 December 2009
- European Parliament: Report on a sustainable EU policy for the High North (Gahler Report) – December 2010
- European Parliament: Resolution on a sustainable EU policy for the High North – January 2011
- European Commission and High Representative of the European Union for Foreign Affairs and Security Policy: Joint Communication to the European Parliament and the Council: Developing a European Union Policy towards the Arctic Region: progress since 2008 and next steps – June 2012
- European Parliament: Resolution on the EU strategy for the Arctic – February 2014
- Council of the European Union: Council conclusions on developing a European Union Policy towards the Arctic Region – Brussels – May 2014.

Making reference to the last resolution of the Council of the European Union (Council conclusions on developing a European Union Policy towards the Arctic Region, 12 May 2014), the Council, based on the European Parliament resolution on the EU strategy for the Arctic of 12 March 2014, recognised, among others, some priority EU commitments:

- Enhancing the EU's contribution to Arctic cooperation;
- Intensifying dialogue on Arctic matters and exploring appropriate ways of ensuring that Arctic indigenous peoples be informed and consulted;
- Enhancing the EU contribution to Arctic scientific research;

Figure 4.1. Sailing in the Ross Sea Antarctic. © Roberto Azzolini

- Ensuring that Arctic-relevant programmes financed by the EU under the 2014-2020 multi-annual financial framework meet the development needs of local populations and offer better opportunities for circumpolar cooperation and research as well as Arctic economic development;
- Working for the further development of an integrated and coherent Arctic Policy by December 2015.

All the above mentioned resolutions stress the strategic interest and mark the roadmap of the European Union for stronger engagement and a coherent policy in the Arctic.

Antarctica

In the last two decades, Antarctica has suffered the rising interest of European governments and trade organisations in the Arctic Regions. The Arctic ice melting is affecting living resources, disclosing new reservoirs of not-living resources, opening cheaper trans-Arctic trade routes: it is creating new economic opportunities but also severe environmental threats.

This new scenario is significantly changing the lifestyle of millions of inhabitants and is raising the demand for scientific knowledge to support political strategies and investments. The European Commission is tackling this trend through strong investment priority addressed to Arctic issues. Consequently, no significant support and devoted funds has been provided by the EU to Antarctic science in the last two decades.

In 2014, Horizon 2020 began to reconsider the relevance of Antarctic science for Europe. Antarctic science is not only linked to the preservation of the global Earth environment, but it is also a strong political commitment of the Antarctic Treaty Consultative (ATC) Countries. By means of the Horizon 2020 Framework Programme the European Commission is now providing the scientific community with an instrument which may allow Antarctic science to be integrated within the European strategy in Polar regions. The instrument is the *Blue Growth* BG-15 call 'European Polar Research Cooperation'.

The BG-15 Call is a bipolar coordination action in the framework of Societal Science, looking at generating a European Polar Scientific Strategy for the next decade, both in the Arctic and in Antarctica.

In December 2014 the European Commission granted the European Polar Board over 2 M€ to manage the EU-PolarNet Project, the European Polar Board application to the BG-15 call. Future calls are expected to be generated upon the results of the EU-PolarNet.

In addition, a number of major scientific organisations are looking to implement excellent science in Antarctica. The following organisations must be mentioned:

- Scientific Committee for Antarctic Research (SCAR). By means of the implementation of the Horizon Scan initiative, SCAR particularly focused on the influences of the poles on global climate and highlighted several overarching priorities.
- Southern Ocean Observing System (SOOS) is a current initiative of relevant interest for the European Polar Board. SOOS is supported by SCAR, Scientific Commission for Oceanographic Research (SCOR), World Climate Research Programme (WCRP), Climate and Cryosphere initiative (CLiC) and Climate and Ocean Variability, Predictability and Change (CLIVAR). SOOS's mission is to coordinate and expand the efforts of all nations and programmes that gather data from the Southern Ocean.
- IPPI (International Polar Partnership Initiative): IPPI should be a platform for coordination and cooperation in achieving socially important goals and common objectives of main polar stakeholders. IPPI will identify synergies between the on-going polar initiatives, find the areas and scope for cooperation between them and support the development of more sustainable polar observations. A Memorandum of Understanding between major polar organisations is envisaged.
- The World Meteorological Organization (WMO) is moving ahead on the Global Cryosphere Watch (GCW), the Antarctic Observing Networks (AntON) and Global Integrated Polar Prediction System (GIPPS) and its components: Polar Prediction Project (PPP) of the World Weather Research Programme (WWRP) and Polar Climate Predictability Initiative (PCPI) of WCRP.

European Polar Board

The European Polar Board (EPB) is the major European polar organisation. It was established by the European Science Foundation, on behalf of the European Commission and the European Committee of Ocean and Polar Science (ECOPS) in 1995, with the task to be the Europe's strategic advisory body on science policy in the Arctic and Antarctica.

Figure 4.2. Skua flying over a leopard seal, Livingston Island, Antarctic. © Alexandre Trindade – Portuguese Polar Programme.

Among its strategic activities the European Polar Board manages the launch and coordination of common initiatives, support to new frontier research, polar science foresight and development of international cooperation.

After its position paper published in 2010, between 2013 and 2014 the European Polar Board published a brochure and several factsheets entitled: *Arctic and Antarctic Science for Europe: the Polar Region in a Connected World*. The publication highlights a number of overarching issues in polar science, technology and infrastructure. They are:

- Improving reliable predictive capabilities, comprehensive environmental research and monitoring of the Polar regions.
- Improving technology and innovation to provide enhanced observational data, reduce logistical costs, and reduce human presence and environmental impact in sensitive ecosystems.
- Baseline documentation of polar marine environments and ecosystems is needed to effectively manage natural resources.
- European assets in the Arctic and Antarctic regions are a very substantial resource with the potential to be used even more effectively.
- Large-scale processes of change in the Polar regions comprise not only environmental dynamics, but also economic, social, political and legal ones. The Arctic and Antarctic offer distinct but sometimes complementary perspectives.

The 4th European Marine Board Forum 'Arctic 2050'

The 4th European Marine Board Forum 'Arctic 2050' was held in Brussels on 12 March 2014. It was a joint European Marine Board and European Polar Board initiative, to discuss how to best manage the consequences of a changing Arctic Ocean.

The forum was attended by delegates from 64 organisations representing a wide range of stakeholders spanning industry (including Shell, GDF Suez, OGP and Total), policy (European Commission and national governments), and academia (research performing and research funding organisations) as well as NGOs and consultancies.

The forum highlighted the following priorities:

- Development of a strategic plan for data collection in the Arctic Ocean: it is urgently needed, along with new observation technologies.
- Development of a marine spatial plan for the Arctic: it is necessary for managing marine and maritime activities.
- More effective use of local and traditional knowledge by engaging indigenous communities in *citizen science* for data collection and ecological management.
- Development of multidisciplinary and cross-sector partnerships in Arctic Ocean research investment in order to secure long-term strategic funding.
- Anticipating infrastructure changes in the Arctic rather than responding to them: shipping industry and associated activities like maritime trade, tourism and transport are likely to emerge faster than the necessary infrastructures for safe, secure and reliable shipping in the Arctic Ocean.

The Transatlantic Alliance and the Galway statement

The Galway meeting took place at the Marine Research Institute in Galway, Ireland, on 23-24 May 2013. The objective was to provide a vision for enhanced cooperation on both sides of the Atlantic and a set of joint agreed priorities to provide the means to achieve these goals. The meeting resulted in the so-called 'Galway Statement on Atlantic Ocean Cooperation'.

The Galway Statement on Atlantic Ocean Cooperation focuses on the Atlantic as a shared international resource and provides an appropriate high-level policy framework for improving international research cooperation across the Atlantic Ocean and into the southern Arctic Ocean. It aims to "increase the knowledge of the Atlantic Ocean and its dynamic systems, including interlinks with the portion of the Arctic region that borders the Atlantic".

The Galway statement looks at the preservation of the ocean and promotes the sustainable management of its resources. It recognises that improving and aligning observations is fundamental to understanding the ocean and forecasting its future. The improvement of coordination of data sharing, interoperability and observing infrastructures and seabed and benthic habitat mapping is recommended as well.

International Conference on Arctic Research Planning – ICARP III

The International Conference on Arctic Research Planning – ICARP III – is an International Arctic Science Committee (IASC) initiative which aimed at:

- Providing a framework to help identify Arctic science priorities for the next decade;
- Coordinating various Arctic research agendas;
- Informing policy makers, people who live in or near the Arctic and the global community;
- Building constructive relationships between producers and users of knowledge.

Referring to the many comprehensive science plans already existing, ICARP III aimed to complement them by identifying and filling gaps that may need attention.

ICARP III has been a process for engaging all partners, including funders, in shaping the future of Arctic research needs, by identifying the most important Arctic research needs for the next decade, providing a roadmap for research priorities and partnerships and identifying potential contributions of Arctic research partners to the International Polar Initiative.

ICARP III culminated in a final conference during the Arctic Science Summit Week (ASSW) 2015 in Toyama, Japan, in junction with IASC's 25th Anniversary.

Comparative Table of International Organisations' Scientific Priorities *vs* ESF *Sailing through Changing Oceans*

(see Table 4.2., pages 84-87)

Table 4.2. Comparison of priorities in ocean and polar life and environment on a warming planet listed by international organisations and by this publication.

AREA	CLAMER	MSFD	JPI Oceans	NFIV
Physical processes at global scale	Ocean/atmosphere interactions and processes during the current rapid warming	Changes in sea temperature and sea-ice cover	Impact of climate change on the ocean circulation patterns, water masses formation and water exchanges, including related feedbacks	Changes in temperature and salinity, stratification, thermohaline circulation (THC), storm frequency and intensity
Palaeoclimate			Role of the ocean in the past as climate regulator	
Sea level and coastal processes	Factors that contribute to spatial variability of sea level rise			Sea level change; Coastal erosion; Ice melting
Carbon cycle and related effects	Response to global warming: implications for carbon sequestration and fish-carrying capacity	Carbon capture and storage (CCS)	Identification of risks and impacts on the marine environment and ecosystems (including coastal areas and shelf processes) associated to sub-seabed carbon storage and sequestration	
Microbial processes	Critical microbial processes contributing to biogeochemical cycling and microbial diversity			
Eutrophication, deoxygenation and related processes	Linkages between eutrophication symptoms and nutrients and effects on living marine resources and health of ecosystems			Ocean deoxygenation and coastal hypoxia Impact of climate change on marine eutrophication
Response of ecosystems to acidification	Response to ocean acidification: benthic and pelagic biota, biogeochemical cycles, links with global warming, sea ice and freshwater runoff in Polar regions	Ocean acidification	Effects of ocean acidification on coastal and shallow marine ecosystems, on pelagic food web dynamics, on biogeochemical and geochemical processes, on the status and functioning of benthic marine ecosystems (including deep sea), on the ecology, distribution and population dynamics in marine ecosystems	Ocean acidification
Impact of changes on ecosystems and living resources	Warming sea temperature impact on biogeochemical cycles, living marine resources, ecosystem resilience and human health		Impact of climate change on biodiversity (including exploitation and invasive species), on the functioning of marine ecosystems and the related value of ecosystem goods and services, including effects on human health	Biodiversity and ecosystems; Biological impacts

UNCSD	IAEA	POLAR (EPB/EMB)	SAILING THROUGH CHANGING OCEANS
			Long -term climatic changes: geologic records from oceans Super warm interglacial periods in the Pleistocene records: sediment cores with model simulations Abrupt climate changes: marine sedimentary and coral records Behaviour of ice sheets during past warm periods
Effects of sea level rise and coastal erosion for coastal regions and islands			Sea level rise and stability of ice sheets: Consequence of sea level rise on thermohaline circulation; Interaction between warm oceanic waters and ice margin
			Past and future effects of oxygenation level on vulnerable European Basins (Baltic, Black Sea, Mediterranean)
Ocean acidification and the impacts of climate change on marine and coastal ecosystems and resources Preventing further ocean acidification, as well as enhancing the resilience of marine ecosystems and of the communities whose livelihoods depend on them Monitoring and observations of ocean acidification and particularly vulnerable ecosystems			Response of reef framework-forming cold-water corals to ocean acidification: improving research on acidifications and connection with marine calcifiers (including corals)
Threats alien invasive species pose to marine ecosystems and resources and need for implementing measures to prevent the introduction of alien invasive species and manage their adverse environmental impacts			Deep-sea biodiversity dynamics and ecosystem stability; relationship between energy sources and biodiversity (associations, mutualisms); role of engineering species, recruitment dynamics and growth rates; response to disturbance Adaptation mechanisms; drivers with a role in polar evolution; relations between adaptations and ecosystems change; Antarctic species adaptation via mutation and gene flow; mechanisms behind species resilience/sensitivity to environmental changes; effect of environmental changes on population performances and species interactions; how much polar species adaptation is weaker than in other species; likely consequences of a changing environment on key ecosystem functions and services How biological data are used for ecological predictions

AREA	CLAMER	MSFD	JPI Oceans	NFIV
Resource exploitation, preservation and related impacts		Impact deriving from a potential use of marine areas for the generation of renewable energy	Understanding and quantification of the effects of climate change and melting of ice in the Arctic, including the assessment of opportunities and risks associated to the opening of the area	
Technologies and methodologies	Functioning of ocean ecosystems as potential platform to apply new technologies and reduce the rising of atmospheric CO_2.		Development of sensors, systems, observatories, methods and models to observe and predict the climate and its changes at different scales, to monitor and assess the status of the marine environment, to predict the ecosystems and biodiversity evolutions in response to changes	
Pollution			Identification of risks and impacts on the marine environment and ecosystems associated to radioactive pollution, marine litter and pollution, oil and gas and gas-hydrates extraction, deep sea mining, noise, geohazards, wind farms and ocean energy, fishing, aquaculture	Riverine discharge and nutrient loads
Strategy, plans, documentation			Development of indicators of the Good Environmental Status (GES) to provide support to the implementation of the EC Marine Strategy Framework Directive	

UNCSD	IAEA	POLAR (EPB/EMB)	SAILING THROUGH CHANGING OCEANS
Assuring conservation and sustainable use of marine biodiversity beyond areas of national jurisdiction; developing and implementing science-based management plans, to maintain or restore stocks (target 2015) Protecting vulnerable marine ecosystems from significant adverse impacts; improving transparency and accountability in fisheries management Vulnerability of coral reefs and mangroves to climate change, ocean acidification, overfishing, destructive fishing practices and pollution Environmental impacts deriving from ocean fertilisation			Ecosystem function and ecosystem services; Improving multidisciplinary studies; Connection with human scientists and policies for a sustainable ecosystem-based management of resource use
Technology transfer based on the Intergovernmental Oceanographic Commission Criteria and Guidelines on the Transfer of Marine Technology	Developing applications of nuclear and isotopic techniques to increase the understanding of oceanic processes, marine ecosystems and pollution impacts More effective use of local and traditional knowledge by engaging indigenous communities in citizen science for data collection and ecological management	Technology and innovation to provide enhanced observational data, reduce logistical costs, and reduce human presence and environmental impact in sensitive ecosystems More effective usage of polar infrastructures and scientific platforms in the Arctic and Antarctic regions It is critical to anticipate the necessary infrastructures for safe, secure and reliable shipping in the Arctic Ocean.	
Marine pollution, including marine debris, especially plastic, persistent organic pollutants, heavy metals and nitrogen-based compounds, from a number of marine and land-based sources, including shipping and land run-off	Conduct studies for the protection of the marine environment from radioactive and non-radioactive pollution		
Assessing the state of the marine environment	Providing expertise, training and reference materials to assist the IAEA member states' commitments to monitor marine environments and promote their sustainable development	Developing reliable predictive capabilities, comprehensive environmental research and monitoring of the Polar regions Engagement with Arctic and Antarctic: changes comprise not only environmental dynamics, but also economic, social, political and legal ones. Arctic and Antarctic offers distinct but sometimes complementary perspectives A strategic plan for data collection in the Arctic Ocean is urgently needed to effectively manage natural resources, along with new observation technologies Developing a marine spatial plan for the Arctic is necessary for managing marine and maritime activities Arctic Ocean research investment requires multidisciplinary and cross-sector partnerships for securing long-term strategic funding	

The First Horizon 2020 Work Programme 2014-2015 and Links to Relevant Ocean and Polar Life Topics

As is widely known, the Horizon 2020 Programme is based on the three pillars 'Excellent Science', 'Tackling Societal Changes' and 'Industrial Leadership': each pillar includes a number of sections hosting different research areas. Calls for the various research areas are posted in the framework of specific biannual work programmes.

Exposed to the inputs of several working groups, international programmes and policy makers, the European Commission approved the Horizon 2020 budget for the period 2014-2020 on 19 November 2013 and a few days later published the draft work programme for the first two years.

With a budget of almost 80 billion € over seven years, Horizon 2020 benefits, in comparison with the 7th Framework Programme, from an increase in financial support of about 30% and is thus the biggest EU Research and Innovation Programme ever launched: in the course of its lifetime Horizon 2020 is expected to attract also a significant contribution of private funding, since it is giving specific opportunities to small and medium enterprises (SME).

The Draft Work Programme 2014-2015 was discussed and approved on 11 December 2013 and the first calls were opened on 12 December 2013 (http://ec.europa.eu/programmes/horizon2020/h2020-sections).

In the next paragraphs, the most relevant calls related to marine and polar environment will be highlighted: some of them are strongly related to the subject of this volume; others are less relevant and could be integrated for enforcing subsidiary topics.

Excellent Science: European Research Infrastructure

Call: Integrating and opening research infrastructures of European interest

INFRAIA-1-2014/2015

This initiative has generated opportunities to develop a platform for future collaborations, promoting Integrating Activities which include networking, transnational and joint research components both for 'Starting Communities' (limited level of networking and coordination) and for 'Advanced Communities' (advanced level of networking and coordination). In this framework the opportunities for environmental and earth sciences target the following research infrastructures: for hydrological/ hydrobiological research; for research on crustal fluids and geo-resources; for long-term ecosystem and socio-ecological research; for ocean drilling; for aerosol, clouds, and trace gases research; for environmental hydraulic research; for terrestrial research in the Arctic; for forest ecosystem and resources research; for integrated and sustained coastal observation.

Within the environmental and earth sciences domain, relevant research infrastructures are:

- Research infrastructures for research on crustal fluids and geo-resources: expected to facilitate synergies between key European analogue experimental, numerical and observational (imaging) facilities, the European Plate Observing System (EPOS) and the International Continental Scientific Drilling Program (ICDP).
- Research infrastructures for long-term ecosystem and socio-ecological research: expected to bring together Long Term Ecological Research (LTER) site-based and properly instrumented facilities and critical zone observatories, covering the widest variety of terrestrial and aquatic environments in Europe (wherever reasonably organised in clusters). These infrastructures are expected also to facilitate the incorporation of long-term socio-ecological research platforms as well as the integration of research field sites, associated data management and numerical simulation tools in order to address threats to soil and water and in particular challenges on urbanisation, land use and food security. The access and services provided have been considered instrumental for researchers to address the broad range of ecosystem research issues (e.g., biodiversity loss, ecosystem services, climate change adaptation and mitigation, land use and management, etc.). Appropriate links with the LIFEWATCH infrastructure for biodiversity research have been welcomed in the Call.
- Research infrastructures for ocean drilling: expected to facilitate the development of a unique EU component for scientific research drilling, promoting integration with the Integrated Ocean Drilling Program (IODP), sharing of technology (drilling and logging, sample and data curation) with ICDP. These infrastructures are also expected to facilitate the link with the European Multidisciplinary Seafloor Observation (EMSO) and other crustal boreholes in creating underground and sub-seafloor observatory networks.
- Research infrastructures for integrated and sustained coastal observation: expected to further harmonise observation techniques in several

European coastal and shelf seas, integrating key observing platforms as well as further developing the collection of biological data, in particular exploiting synergies with marine biological observatories. These infrastructures are also expected to facilitate the link with appropriate European Strategy Forum on Research Infrastructures (ESFRI) projects such as EURO-ARGO, EMSO and EMBRC and aim at a single European channel for all physical, chemical and biological coastal data.

Call: Support to innovation, human resources, policy and international cooperation

Within Horizon 2020 European Research Infrastructures, the Call/Support to innovation, human resources, policy and international cooperation may have been considered as a relevant call fitting the priorities of this volume, including polar priorities, in terms of supporting infrastructures.

INFRASUPP-6-2014: International cooperation for research infrastructures

This call has supported multi-lateral cooperation on research infrastructures in one or several of the following areas: Arctic research, marine science, biodiversity, food research and medicine. Particular emphasis has been put on cooperation with USA, Canada (including the implementation of the Transatlantic Research Alliance launched by the Galway Statement on Atlantic Ocean Cooperation) and Russia, without excluding other relevant Countries such as Australia and New Zealand.

INFRASUPP-8-2014: Network of National Contact Points

This call has aimed at facilitating transnational cooperation between NCPs for research infrastructures with a view to identifying and sharing good practices and raising the general standard of support to programme applicants, taking into account the diversity of actors that make up the constituency of the research infrastructures part.

Societal Science: Food Security, Sustainable Agriculture and Forestry, Marine, Maritime and Inland Water Research and the Bioeconomy

Call for Blue Growth

When looking at the calls promoting research linked to the theme of ocean and polar life and environment on a warming planet, it is evident that the main area of opportunities has been offered by the 'Call for Blue Growth: unlocking the potential of Seas and Oceans', part of the area of 'Food security, sustainable agriculture and forestry, marine and maritime and inland water research and the bioeconomy', falling under the pillar 'Tackling Societal Challenges'.

The Call for Blue Growth has addressed five cross-cutting priority domains:

- Valorising the diversity of marine life
- Sustainably harvesting deep-sea resources
- New offshore challenges
- Ocean observation technologies
- The socioeconomic dimension.

As specified in the text of the Work Programme 2014-2015, Blue Growth has aimed to improve the understanding of the complex interrelations between various maritime activities, technologies, including space enabled applications, and the marine environment in order to help boost the marine and maritime economy by accelerating its potential through research and innovation.

The calls 2014 on the sustainable exploitation of the diversity of marine life have put emphasis on valuing and mining marine biodiversity, while the calls 2015 have focused on the preservation and sustainable exploitation of marine ecosystems and climate change effects on marine living resources.

The new offshore challenges have been tackled in 2014 through a support action (CSA) preparing potential further large-scale offshore initiatives and one initiative focused on sub-sea technologies. In 2015 a large-scale initiative has been planned in response to oil spill and maritime pollution.

Regarding ocean observation, a large-scale initiative on improving systems/technologies including novel monitoring systems for *in situ* observations, as well as one activity on acoustic and imaging technologies have been supported in 2014.

In terms of international cooperation, the 'Blue Growth' Focus Area has supported the new Atlantic Ocean Cooperation Research Alliance launched by the Galway Statement in May 2013.

Specific themes of interest for progressing in the understanding of ocean and polar life and environment on a warming planet have been or will be offered under:

BG-1-2015: Improving the preservation and sustainable exploitation of Atlantic marine ecosystems

The call has focused on the North Atlantic, seen as a key marine region that encompasses ecologically and biologically important and fragile ecosystems (e.g., deep cold-water corals) and provides goods and services essential for populations' well-being such as regulating climate.

The call has especially encouraged proposals aiming to fill the knowledge gaps in the understanding of the biogeographic patterns, biodiversity, biogeochemistry and ecosystem services and goods supported by different marine ecosystems at ocean basin scales.

BG-2-2015: Forecasting and anticipating effects of climate change on fisheries and aquaculture

The call has focused on global warming and climate change, which are likely to affect all the components of the biosphere and impact the functioning of all aquatic ecosystems and the living organisms that populate them.

The call has promoted proposals capable of putting similar emphasis on understanding how climate change may affect the most important and less resilient exploited European fish stocks and on investigating the potential effects and consequences of climate change on aquaculture. Proposals taking into account the diversity of aquaculture practices, species and regional specificities, farming technologies and specific requirements of established and emerging European farmed species have been encouraged.

BG-6-2014: Delivering the sub-sea technologies for new services at sea

The call has addressed the development of unmanned underwater operation tools (AUV, ROV) to enable sustainable and safe offshore operations by European industries in extreme conditions (e.g., deep sea areas, Arctic conditions, etc.).

BG-7-2015: Response capacities to oil spills and marine pollutions

The call addressed the pollution of seas and oceans with specific focus on predicting and measuring the evolution of the pollution (e.g., oil spill, chemical pollution) and designing an appropriate response combining the right mix of interventions.

Under this theme the call aimed at developing an integrated operational response capacity to major offshore and/or coastal pollution events (particularly oil and gas), including in extreme oceanic conditions. The call has promoted an integrated approach combining the oceanographic prediction of the pollution behaviour, the understanding of the pollution impact (including the role of marine microbial communities), the use of physical, chemical and biological remediation (including its impact on ecosystems) and the use of specialised vessels and underwater (autonomous) vehicles. The call has thus encouraged proposals capable of improving the European operational response capacity to pollution, in particular by using integrated models and tools that can be tested for a better preparedness and support decision making in the management of such type of events. The call has also generated links and opportunities of synergies for proposals addressing the protection of sensitive ecosystems in high risk areas.

BG-8-2014: Developing in situ Atlantic Ocean Observations for a better management and sustainable exploitation of the maritime resources

The call focused on conducting research and innovation activities aiming to deploy an Integrated Atlantic Ocean Observing System (IAOOS), building on existing capacities on both side of the Atlantic. The acquisition and use of *in situ* observations and their integration with remote sensed data across the whole Atlantic Ocean in order to fill out the existing observational gaps have been considered as a key component for the development of IAOOS.

The call has thus promoted proposals covering the whole Atlantic with the objective of understanding ocean processes at the level of the entire basin and facilitating the interoperable exchange of Atlantic Ocean observation as promoted through the Group on Earth Observation (GEO).

BG-13-2014: Ocean literacy – Engaging with society – Social Innovation

The call focused on achieving a sustainable exploitation of marine resources and a good environmental status of seas and oceans through the awareness of citizens of the influence of seas and oceans on their lives and of how their behaviour could have an impact on marine ecosystems.

The call encouraged proposals aiming at compiling (and, later, disseminating) existing knowledge in the broad area of 'Seas and Ocean Health' (environmental status, pollution affecting marine biodiversity and ecosystems, ecosystem services) including the impact on citizens and human health.

BG-14-2014: Supporting international cooperation initiatives: Atlantic Ocean Cooperation Research Alliance

The call focused on the importance of marine and maritime scientific and technological cooperation in building dialogue, sharing knowledge and mutual understanding between different scientific communities, cultures and societies.

The call has promoted proposals aligned with the objectives of the EU strategy for International Cooperation in Research and Innovation, capable of contributing to the implementation of the Transatlantic Research Alliance, launched by the Galway Statement on Atlantic Ocean Cooperation in May 2013. The inclusion of partners from the US and Canada has been encouraged. The call has specifically encouraged proposals addressing the development and integration of six priority areas identified in the Galway Statement:

(1) Marine ecosystem-approach, (2) Observing systems, (3) Marine biotechnology, (4) Aquaculture, (5) Ocean literacy – engaging with society, (6) Seabed and benthic habitat mapping.

The mapping and connectivity of relevant ongoing research activities and programmes in the Atlantic, the identification of research gaps and the integration with the existing efforts to generate a European Marine Observation and Data Network (EMODNet) have been considered as key elements for the successful proposals submitted under this call.

BG-15-2014: European polar research cooperation

The call focused on the effects of climate change, which is more evident at high latitudes and requires sound scientific knowledge of vulnerabilities and risks in polar areas in order to develop appropriate regulatory policies.

It is worth noting that the call has not offered any type of direct funding for research on the effects of climate change: it has rather promoted the generation of a cooperation platform capable of launching in the future synergies for addressing specific scientific themes related to climate change.

This call has thus promoted the development of a comprehensive European Polar Research Programme aiming at setting up a continuous stakeholder dialogue which would communicate user needs to the appropriate scientific community and/or research programme managers. The call has also aimed at contributing to the implementation of the Transatlantic Research Alliance (launched by the Galway Statement on Atlantic Ocean Cooperation in May 2013), to the inclusion of partners from the US, Canada and other Countries, and to the enhancement of coordination with international research organisations and programmes related to polar research.

Societal Science: Climate Action, Environment, Resource Efficiency and Raw Materials

Call: Growing a Low Carbon, Resource Efficient Economy with a Sustainable Supply of Raw Materials

Additional opportunities to develop research linked to the theme of ocean and polar life and environment on a warming planet and in close connection with climate change issues have been offered under the Call 'Growing a Low Carbon, Resource Efficient Economy with a Sustainable Supply of Raw Materials', part of the area of 'Climate action, environment, resource efficiency and raw materials', falling under the pillar 'Tackling Societal Challenges'.

SC5-1-2014: Advanced Earth-system models

The call focused on a new generation of advanced and well-evaluated global climate and Earth-system models and related prediction systems capable of providing governments, business and society with actual and trustworthy scientific input. Such input should help formulate climate risk assessments at decadal to centennial time scales with the highest possible spatial resolution.

The call has promoted proposals incorporating physical, chemical and biological Earth-system processes into climate models predictions and projections at the appropriate scale. Proposals presenting advanced high resolution Earth-system models capable of providing the basis for producing novel climate scenarios have been encouraged. Support has also been given to proposals developing a better understanding of past and recent climatic variability and its causes and impacts on societies, resources and ecosystems.

The outcome of this call has targeted the post-AR5 Intergovernmental Panel for Climate Change (IPCC) process and other relevant international scientific assessments, aiming to provide a solid scientific basis for future science cooperation and policy actions at European and International level.

SC5-2-2015: European Research Area (ERA) for climate services

The call focused on generating financial resources from national (or regional) research programmes in view of implementing a joint call for proposals with EU co-funding: proposals linked with international climate service initiatives and developing better tools, methods and standards for producing and using data related to future climate variability and extreme conditions for specific regions and relevant time periods (seasonal-to-decadal) at regional and local scale have been encouraged.

SC5-5-2014/2015: Coordinating and supporting research and innovation for climate action

The call focused on a more robust integration and coordination of ongoing and future climate change research and innovation initiatives (within the EU and beyond) aiming to help EU businesses and citizens understand the state of the climate, the possible response options and their consequences for society, economy and environment.

EU climate change networks capable of facilitating the dialogue among the relevant scientific communities, funding bodies and user communities in the EU have been encouraged. Dissemination activities targeting different stakeholders and increasing public awareness about climate science and research results have been an important component of this call.

In this framework a key component has been the development of clustering, coordination and synergies between international, cross-disciplinary, EU and nationally funded climate change research and innovation actions, with the multiple aims of developing joint programmes and projects, creating links with related international programmes and strengthening the science-policy interface.

The main priority of the 2014 call has been Climate Change Mitigation, while the call for 2015 has promoted the Earth-system modelling and climate services components.

SC5-6-2014: Biodiversity and ecosystem services: drivers of change and causalities

The call focused on the knowledge gaps in understanding the causality relationships between drivers/pressures and changes in biodiversity, ecosystem functions and ecosystem services and their impacts on society and resilience.

Key aspects of this call have included scientific themes such as:

1. Causalities between biodiversity and ecosystem functions and services
2. Impacts of direct, indirect and emerging drivers of change in biodiversity, ecosystem function, resilience and service provision
3. Forecasting methodologies to predict future variation in drivers of change and their expected impact on biodiversity
4. Development and refinement of sound and cost-effective indicators on biodiversity, ecosystem function/resilience and ecosystem service
5. Development of innovative concepts for ecosystem service and of common frameworks and tools for the conservation and sustainable management of biodiversity and ecosystem services.

The outcome of this call is expected to contribute to the achievement of EU and international biodiversity targets (EU 2020 Biodiversity Strategy, Convention on Biological Diversity, Rio+20) and to promote links with international efforts and fora on biodiversity and ecosystem services.

SC5-9-2014: Consolidating the European Research Area on biodiversity and ecosystem services

The call focused on advancing towards the completion of the European Research Area in biodiversity and ecosystem services, enhancing coordination and assuring sustainable development. The ultimate target of this action has been the realisation of a unified and open biodiversity research area promoting free circulation of scientific knowledge and technology and strengthening competitiveness.

The call has promoted the generation of financial resources from national (or regional) research programmes in view of implementing a joint call for proposals with EU co-funding to develop a joint vision and a common strategic research agenda for biodiversity and ecosystem services, involving also social sciences and humanities, as appropriate.

SC5-15-2015: Strengthening the European Research Area in the domain of Earth observation

The call focused on bringing together and strengthening European national and regional research and innovation programmes in the domain of Earth observation, avoiding fragmentation.

Joint proposals with EU co-funding were encouraged to develop the observation and monitoring of changes affecting the Earth's atmosphere, oceans, cryosphere and landscapes, with human activities being a major driver of these changes in the domain of climate, environment and resource efficiency.

The call has strongly promoted links to the agenda (current and post-2015) of the Global Earth Observation (GEO), of the Copernicus Programme and of other pan-European organisations conducting research activities in the domain of Earth observation, such as the European Space Agency. Key elements of this call have been data sharing and interoperability amongst observations, modelling, data assimilation and prediction systems and supporting decision making in the domains of climate, environment, resource efficiency and natural hazards.

SC5-16-2014: Making Earth observation and monitoring data usable for ecosystem modelling and services

The call focused on the collection and availability of Earth observation data and information when developing terrestrial and marine ecosystem models and sustainable ecosystem services, in order to deliver major benefits to citizens, businesses and governments. Innovative solutions capable of providing open and unrestricted access to interoperable ecosystem Earth observation data and information have been highlighted as a key component of this call.

The call has, in particular, supported proposals focusing on recovering existing data, supporting new measurements and observations, synthesising and interpreting data in order to make all information and knowledge available to scientists, policy makers, citizens and other concerned stakeholders. One of the expected results has been a full picture of the state and temporal evolution of ecosystems in existing internationally recognised protected areas.

Through the promotion of the participation of pan-European organisations linked to Earth observation, the call has highlighted the need for generating synergies and avoiding duplication with other international actions (e.g., European Space Agency (ESA) Climate Change Initiative and Copernicus Global Monitoring for Environment and Security).

SC5-19-2014/2015: Coordinating and supporting research and innovation in the area of climate action, environment, resource efficiency and raw materials

The call focused on improving transnational cooperation and coordination of research and innovation policies, programmes and initiatives in the area of climate action, environment, resource efficiency and raw materials.

The call has promoted proposals enhancing coordination and synergies and avoiding overlaps between European and nationally or regionally funded research and innovation actions, creating links with related international programmes, as appropriate. The final target of this call has been reinforcing of European networks in order to facilitate dialogue among the relevant scientific communities, funding bodies and user communities in the EU throughout the duration of Horizon 2020.

Call: Water Innovation: Boosting its value for Europe

WATER-2-2014/2015: Integrated approaches to water and climate change

The call focused on the forecasting of natural water cycle variability and extreme weather events in the short and medium term and on the need for improved understanding of the impacts of climate change on the hydrological cycle in order to better inform decision makers and ensure sustainable water supply and management of water systems, and quality of water bodies within the EU.

Proposals including reliable forecast of the hydrological cycle changes versus the predicted warm climate and high CO_2 atmosphere value and incorporating estimates (rates and amount of changes) of continental ice sheet melting and ocean thermohaline circulation changes impacting precipitation have been strongly encouraged.

The first two stages of the action WATER-2-2014 have aimed to study the water cycle under future climate, focusing on reliable projections of precipitation in relation to water cycle variability at local and regional scales in Europe over various timescales, including the forecasting of extreme events and the development of risk management strategies.

The two 2015 stages have focused on the development of a better scientific understanding of the land-water-energy-climate nexus and of integrated approaches to food security, low-carbon energy, sustainable water management and climate change mitigation.

Call: Secure societies – Protecting freedom and security of Europe and its citizens

Some opportunities to develop research linked to the theme of ocean and polar life and environment on a warming planet might have found a niche also under the call 'Disaster Resilience & Climate Change', part of the area 'Secure societies – Protecting freedom and security of Europe and its citizens', falling under the pillar 'Tackling Societal Challenges'.

DRS-9-2014/2015: Disaster resilience and climate change topic 1: Science and innovation for adaptation to climate change: from assessing costs, risks and opportunities to demonstration of options and practices

The call focused on the coordination and the clustering of research and innovation activities on climate change impacts, vulnerabilities and adaptation in different sectors, also in relation to long-term risk reduction from extreme weather events.

The Innovation Actions 2015 have offered areas of development for proposals aiming to support, test and disseminate technological and non-technological options, including eco-system based approaches, to address climate-related risks and climate-proof critical infrastructure assets and systems.

Dynamics of the Ocean and Polar Environment in a Warming Planet

Scientific Priorities

In Chapter 2 of this publication the main priorities and open scientific questions related to the dynamics of the oceans and polar environments in a warming planet have been discussed and highlighted: how many of these priorities have been addressed through one of the 2014/2015 Horizon 2020 Calls / Actions and how many such priorities are still in need of further areas of opportunity in the forthcoming new Horizon 2020 calls?

Fabio Florindo and Stephen Pekar highlight how **geological records provide a backdrop which helps understand the relationships between climate changes and carbon cycling today.** Periods of high concentration of greenhouse gases and global temperatures in the past provide examples of how the Earth operated under such a climate. **The collection (through ocean, land and ice-based drilling programmes) and exploitation of geological archives are, therefore, two key elements to assess the environmental changes observed nowadays and to project them in the future**.

Dick Kroon concurs with the main conclusions of Fabio Florindo and Stephen Pekar and indicates **the use of sediment cores combined with model simulations as a robust instrument to investigate causes and effects of climate warming in the North Atlantic and in the Arctic**.

In line with the previous authors, Dierk Hebbeln looks with great interest to a **global database collecting information on past abrupt climate changes** and puts **high on the research agenda the collection and analyses of marine sedimentary and coral records**.

Laura De Santis discusses **how peri-Antarctic drilling could reveal the way ice sheets have behaved in past periods of high temperature and high atmospheric CO_2 content.** She also highlights the contribution of peri-Antarctic drilling in the process of understanding **how grounded ice had responded to warming oceanic waters and to what extent the large freshwater discharges in a warming climate had impacted sea level and the thermohaline circulation**.

Gert J. De Lange highlights how **some of the ocean sub-basins, ranking among the most vulnerable on Earth, are within the European realm: the Baltic, the Mediterranean and the**

Figure 4.3. The Greatship Manisha, drillship of IODP Expedition 347 is equipped with the drill rig Geoequip Marine's GMTR 120 Geotechnical and Coring Rig (photo Geoequip Marine, courtesy of Island Drilling Singapore Pte.Ltd).

Black Sea. These seas have impacted in different ways climate zones and environmental conditions: thus **the three seas offer a unique opportunity for conducting integrated studies on any change (with special focus on oxygenation levels) which might impact their equilibrium, the biodiversity and the human use of the seas** (including **fisheries and recreation**).

In conclusion, Chapter 2 highlights the importance of obtaining and exploiting geological archives (including marine sediments and coral records with decadal or higher temporal resolution) in highly sensitive areas at different latitudes in order to assess the present and future environmental changes on Planet Earth through appropriate models.

Areas of Opportunities in the first Calls and Actions of Horizon 2020

The 2014-2015 Calls of Horizon 2020 have provided some general support for the above mentioned priorities and scientific communities through the call for infrastructures **INFRAIA-1-2014/2015.**

This initiative, as previously mentioned, has generated opportunities to develop a platform for future collaborations, promoting integrating activities which include networking, transnational and joint research components both for 'Starting Communities' (limited level of networking and coordination) and for 'Advanced Communities' (advanced level of networking and coordination).

For the specific priorities described in Chapter 2 opportunities have been offered under the areas:

- Research infrastructures for ocean drilling and
- Research infrastructures for integrated and sustained coastal observation.

The added value embedded in this call consists in the promotion of consortia aiming to share technologies, samplings and data collected in the vulnerable areas of oceans, of the oceans' bottom floors and of coastlines: this approach has offered the scientific community the opportunity of gathering valuable information which would be otherwise difficult to be gathered by individual institutions or research groups.

The calls **WATER-2-2014/2015** (Integrated approaches to water and climate change)**, SC5-1-2014** (Advanced Earth-system models), **SC5-2-2015** (ERA for Climate Services), **SC5-5-2014/2015** (Coordinating and supporting research and innovation for climate action), **SC5-15-2015** (Strengthening the European Research Area in the domain of Earth observation) and **SC5-19-2014/2015** (Coordinating and supporting research and innovation in the area of climate action, environment, resource efficiency and raw materials) have commonly offered additional opportunities for the specific scientific priorities highlighted in Chapter 2. The common aim of these calls has been to provide trustworthy scientific input to climate risk assessments at decadal to centennial time scales at the highest spatial resolution possible by using advanced high resolution Earth-system models. The calls have promoted also the consolidation of the European Research Area in Earth Observation.

In conclusion, the collection of geological samples to populate a large database, the study of marine and coral records, the study of palaeoclimate to help model the current climate changes observations might have found a niche in one or more of such calls. However, the large spectrum of the calls and the likely large number of applications with multiple targets in this remit might also have generated a platform not properly tailored for the development of specific studies on palaeoclimate.

Relevant Scientific Topics in need of new Horizon 2020 Calls

The priorities indicated in Chapter 2 of this publication are very much aligned with the 2013 Report of the Intergovernmental Panel on Climate Change (IPCC), which highlights that the atmospheric concentrations of the greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have all increased since 1750 due to human activity. In 2011 the concentrations of these greenhouse gases were 391 parts per million (ppm), 1803 parts per billion (ppb) and 324 parts per billion, exceeding the pre-industrial levels by about 40%, 150% and 20%, respectively. Atmosphere and ocean warming have been observed, the amounts of snow and ice have diminished, the level of seas has risen and the concentration of greenhouse gasses has increased. In this scenario the IPCC Report states that warming of the climate system is unequivocal, leading to observed changes since 1950 which are unprecedented over decades to millennia.

Specific Horizon 2020 Calls supporting international drilling programmes and addressing the acquisition of data on palaeoclimate at high, mid and low latitudes, including the past impacts on thermohaline circulation, carbon sequestration and CO_2 storage would be thus instrumental to support the continuous efforts made by IPCC to monitor the key indicators for climate change.

Dynamics of the Ecosystems under Global Change

Scientific Priorities

Chapter 3 describes the open scientific questions and consequent research priorities related to the dynamics of ecosystems under global change: similarly to Chapter 2, how many of such priorities have been addressed through one of the 2014/2015 Horizon 2020 Calls / Actions and how many such priorities are still in need of further areas of opportunities in the forthcoming new Horizon 2020 calls?

In Chapter 3, **Nadine Le Bris** highlights the importance of habitats, species and gene diversity in deep-sea systems. **Extreme environments** provide unique **natural models to understand the mechanisms which establish and maintain biodiversity in deep-sea ecosystems. Key issues** to be addressed to progress in the understanding of deep-sea habitats include the **relationship between energy sources and biodiversity**, the **role of engineer species, recruitment dynamics and growth rates** and the **response to disturbances**.

Marina R. Cunha discusses the fundamental **aspects of deep-sea biodiversity and ecosystem function in relation to our changing planet**: the understanding of **habitats, species, gene diversity of deep-sea systems and ecosystem connectivity in the oceans** will help determine the effects of climate change and/or human exploitation on marine ecosystems.

Eva Ramirez-Llodra and **Maria C. Baker** describe the **unique attributes of deep-sea ecosystems and the services they provide,** engaging the reader in an overview and discussion of current impacts faced by one of the last pristine biomes in Planet Ocean. The increasing use of deep-sea services, ocean acidification and climate change impact ecosystems and biodiversity. The authors indicate as **imperative to continue to explore and study deep-sea environments using interdisciplinary and ecological approaches**.

J. Murray Roberts highlights how **acidification caused by increasing anthropogenic CO_2 affects the oceans by inducing a decline of sea water PH and substantial modifications in cold-water corals**. The author recommends to **develop long-term experiments to assess the effects of temperature changes, ocean acidification and multiple stressors on marine ecosystems**.

In the final essay of Chapter 3, **Cinzia Verde**,

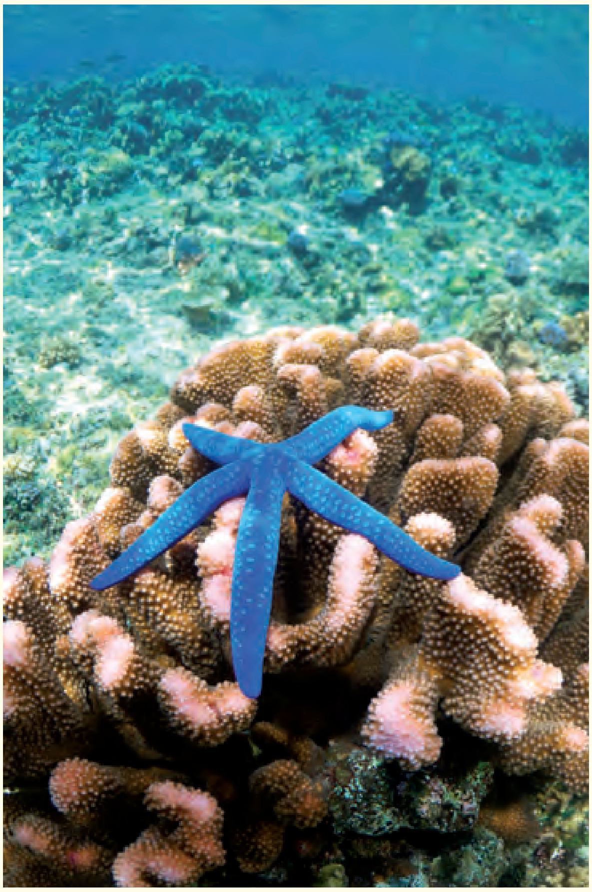


Figure 4.4. Blue starfish, coral reef. © iStock

Guido di Prisco, Melody S. Clark, Lloyd S. Peck and Federico M. Lauro highlight the **vulnerability of polar ecosystems** and focus on the **potential cumulative effects of climate change on organism physiology, populations of individual species, community composition and biodiversity**. The authors propose as a priority a **set of key questions to address the impact of stressors on key ecosystem functions and services of polar marine ecosystems**.

Areas of Opportunities in the first Calls and Actions of Horizon 2020

The 2014-2015 Calls of Horizon 2020 have provided some general support to the priorities described in Chapter 3 through **BG-1-2015** (Improving the preservation and sustainable exploitation of Atlantic marine ecosystems), **BG-2-2015** (Forecasting and anticipating effects of climate change on fisheries and aquaculture), **BG-7-2015** (Response capacities to oil spills and marine pollutions), **BG-8-2014** (Developing *in situ* Atlantic Ocean Observations for a better management and sustainable exploitation of the maritime resources), **BG-13-2014** (Ocean literacy – Engaging with society – Social Innovation), **BG-14-2014** (Supporting international cooperation initiatives: Atlantic Ocean Cooperation Research Alliance), **SC5-6-2014** (Biodiversity and ecosystem services: drivers of change and causalities), **SC5-9-2014** (Consolidating the European Research Area on biodiversity and ecosystem services), **SC5-16-2014** (Making Earth observation and monitoring data usable for ecosystem modelling and services).

Some of the topics proposed as top priorities by the authors of Chapter 3 have certainly found a niche, in particular under the call SC5-6-2014, addressing the need for documenting and evaluating the effects of drivers of change on all relevant levels of biological organisation: this call aims to better understand the links between biological diversity, ecosystem functions and resilience and ensure effective policy and sustainable development.

Nevertheless, a large number of priorities are still in need of further development.

Relevant Scientific Topics in need of new Horizon 2020 Calls

The scientific experts of dynamics of the ecosystems subject to global change are still in need of additional opportunities to develop their research priorities. The systematic study of long-term effects of stressors on marine ecosystems entails the acquisition of a large amount of data and the population of large databases with key indicators associated to global and anthropogenic changes. Funding should thus be available to generate consortia addressing the responses of marine ecosystems and biodiversity to changes at high, medium and low latitudes and to support data acquisition, data mining and modelling of deep-sea and marine ecosystems and biodiversity.

The intrinsic multidisciplinary nature of studies on marine and deep-sea ecosystems and biodiversity would certainly facilitate the formation of multidisciplinary consortia and the population of complete datasets, capable of supporting enhanced models for ecosystems.

The study and understanding of long-term impacts of global and anthropogenic changes on marine ecosystems would undoubtedly bring a benefit not only to the preservation of biodiversity and ecosystem services, but will also contribute to a key societal issue, highlighted by the European Commission and numerous international organisations: the sustainable exploitation of marine ecosystem services.

Marine Polar Research

Scientific Priorities

The ESF *Sailing through Changing Oceans* (see Chapter 2 and Chapter 3) has highlighted several scientific priorities on *Dynamics of the Ocean and Polar Environment* and *Dynamics of the Ecosystems under Global Change*. Most of these priorities may be related either to polar areas or to other latitudes since the phenomena they focus on may be referred to different latitudes and environmental conditions: a general description on how these priorities have been considered in the 2014-2015 Horizon 2020 Work Programme has already been provided in this chapter.

However, several of these priorities specifically concern polar areas. This group of priorities includes topics such as climate change effects on polar marine species, ice melting, genetic, biochemical and physiological mechanisms of adaptation, polar ecosystem ecology and services.

Making reference to Chapters 2 and 3, the priorities more clearly related to the Polar regions may be listed as follows.

- Long-term climatic changes: improving campaigns and technology to achieve a greater amount of geographically distributed geologic records from polar oceans.

Figure 4.5. Taking seawater samples near Rothera Research Station, Antarctica. © Pete Bucktrout, British Antarctic Survey

- Abrupt climate changes: improving collection and analyses of polar marine sediments.
- Sea level rise and stability of ice sheets: improving observations, including satellite observations, and international cooperation surveys are needed particularly focusing on the behaviour of ice during past warm periods, the consequence of sea-level rise on thermohaline circulation and the interaction between warm oceanic waters and ice margins.
- Improving multidisciplinary research and field campaigns focused on past and future effects of oxygenation level on vulnerable Arctic European Basins.
- Stresses on polar marine ecosystems: impact on key ecosystem function and services. Improving multidisciplinary studies focused on
  - Ecosystems such as cold-water coral reefs and hydrothermal vents that are vulnerable to the impacts of climate change and human activities;
  - Adaptation mechanisms, included Antarctic species adaptation via mutation and gene flow; how much polar species adaptation is weaker than in other species;
  - Relation between adaptations and ecosystems change, included mechanisms behind species resilience/sensitivity to environmental changes;
  - Drivers with a role in polar evolution;
  - Effect of environmental changes on population performances and species interactions; likely consequences of a changing environment on key ecosystem functions and services; ranging of ecosystem tipping points.

These priorities will be mentioned as *Polar Science priorities* in the following.

Areas of Opportunity in the Horizon 2020 Calls 2014-2015

Beside two cases that will be discussed later, the Work Programme 2014-2015 of Horizon 2020 did not explicitly consider polar research in any of its calls. The two only exceptions are the Call Blue Growth-15 'European Polar Research Cooperation', within the Societal Challenge 'Food Security, Sustainable Agriculture and Forestry, Marine, Maritime and Inland Water Research and the Bioeconomy', and the Call INFRASUPP-6-2014, within the Excellence Science Call Support to innovation, human resources, policy and international cooperation: the former is a coordination action dealing with both Arctic and Antarctic research, the latter expressly refers to Arctic infrastructure also

Figure 4.6. The research vessel Polarstern is used for support of the Antarctic stations. Here, container, equipment and fuel are unloaded on the sea ice of the Atka Bay close to the Neumayer station. © Hannes Grobe/Alfred-Wegener-Institut

in the framework of the Galway Statement for the Transatlantic Research Alliance between Europe, the USA, Russia and Canada.

However, even if not extensively supporting polar activities, the Work Programme 2014-2015 has taken into consideration several topics which are definitively linked and interconnected with polar research. These topics have been addressed by calls focusing on global scale phenomena which may integrate Polar regions into the global scenario as a crucial element of the investigated processes. In this framework, an additional key element of the Horizon 2020 Excellent Science pillar is the support to scientific infrastructures in relevant fields such as palaeoclimate, abrupt climate and biological research.

The opportunities offered by the first Horizon 2020 Work Programme for the priorities identified under Chapters 2 and 3 for the polar marine areas will be briefly discussed hereafter. Next, the scientific areas and topics which are still in need of finding a niche in the forthcoming Horizon 2020 Work Programmes will be highlighted.

European Research Infrastructure

In Chapter 2 it is highlighted that research on long-term climatic changes, super warm interglacials in the Pleistocene as well as abrupt climate changes requires geologic records from polar oceans that can be obtained from marine sediments by drilling the oceanic bottom floor.

Within the Horizon 2020 Work Programme 2014-2015 the European Research Infrastructures area has met the above-mentioned needs through the Call 'Support to innovation, human resources, policy and international cooperation'.

In this framework, ***INFRASUPP–6–2014:*** *International cooperation for research infrastructures*, has addressed, among others, multilateral cooperation on research infrastructures in Arctic research, marine science, biodiversity and food research with particular emphasis on cooperation with the USA, Canada (included the Transatlantic Research Alliance, launched by the Galway Statement on Atlantic Ocean Cooperation) and Russia, without excluding other relevant Countries such as Australia and New Zealand.

An additional relevant call has been ***INFRASUPP-8-2014*** *– Network of National Contact Points*. The call aimed at facilitating transnational cooperation to identify and share good practices for managing research infrastructures with a view to improve the general standard of support to programmes.

Making reference to polar sciences priorities, the Call ***INFRAIA-1-2014/2015:*** *Integrating and opening existing national and regional research infrastructures of European interest*, may have met polar science needs by bringing together, integrating on European scale, and opening to all European researchers key national and regional research infrastructures, facilitating their optimal use and joint development.

The call has taken into consideration several kinds of infrastructures, among which the European research infrastructures for ocean drilling. It has aimed at integrating the Integrated Ocean Drilling Program (IODP), the International Continental Scientific Drilling Program (ICDP), the European Multidisciplinary Seafloor Observation (EMSO) and other crustal boreholes, for developing European capacity in this field.

Looking at polar scientific priorities related to polar marine ecosystems, the call has also addressed research infrastructures for long-term ecosystem and socio-ecological research. These topics, even if not specifically oriented towards the Arctic marine system, have potentially allowed the inclusion of polar priority topics into the long-term socio-ecological research platforms and into the research areas addressing a broad range of relevant ecosystems related issues, such as biodiversity loss, ecosystem services, climate change adaptation and mitigation, land use and management, etc.

The Call for Blue Growth

The Call for Blue Growth, within Societal Challenge *Food Security, Sustainable Agriculture and Forestry, Marine, Maritime and Inland Water Research and the Bioeconomy* has been the primary action for supporting polar science priorities, as indicated in the previous discussion for Chapters 2 and 3. However, among its several sub-calls, only ***BG-15-2015****, European Polar Research Cooperation*, may be considered as purely polar oriented and has aimed at creating the strategy, the links and the appropriate international liaisons for future EC Calls in Polar Science.

The call ***BG-15-2014****: European Polar Research Cooperation*, has focused on vulnerabilities and risks in polar areas related to climate change, which become more evident at high latitudes: this challenge requires sound scientific knowledge in order to develop appropriate regulatory policies. Through rather limited funds this call has not supported research but rather has promoted a cooperation platform capable of launching in the future synergies for addressing specific scientific themes related to climate change. The call has aimed at facilitating the implementation of the Transatlantic Research Alliance according to the Galway Statement on Atlantic Ocean Cooperation signed in May 2013.

In the framework of Horizon 2020 BG 15-2014 Call on European Polar Research Cooperation, the European Commission has recently funded the European Polar Board application EU-PolarNet – Connecting Science with Society. With 22 partners from 17 nations with support from 16 international organisations EU-PolarNet aims to develop an integrated European polar research programme in cooperation with all relevant stakeholders and international partners. This European polar research programme will also provide European governments with a consistent scientific platform to design policy measures to mitigate the climate change effects and to make society capable of benefitting from the opportunities that are opening up in the Polar regions.

Among the various sub-calls of Blue Growth, ***BG-2-2015*** *– Forecasting and anticipating effects of climate change on fisheries and aquaculture* – may be mentioned. The call has met the Cap 3 scientific priorities, since it has focused on the effects of global warming and climate change which affect all the components of the biosphere and impact the functioning of all aquatic ecosystems and the living organisms that populate them. However, the call has been primarily focused on understanding how climate change may affect the most important and less resilient exploited European fish stocks and on investigating the potential effects and consequences of climate change on aquaculture: these topics are not polar priorities and are not part of the core topics of this volume.

From a technological point of view, ***BG 6 – 2014*** *– Delivering the sub-sea technologies for new services at sea* – has been very relevant to polar science. The 'Hausgarten' underwater observatory, part of the European HERMES Project, followed by the HERMIONE Project, is a significant example of scientific use of unmanned underwater means. This call has definitively met the need of improving polar and deep-sea exploration capacity by developing unmanned underwater operation tools (AUV, ROV) to enable sustainable and safe offshore operations in extreme conditions.

Within the observational capabilities, ***BG-8-2014****: Developing* in situ *Atlantic Ocean Observations for a better management and sustainable exploitation of the maritime resource*s, has provided support in developing *in situ* Atlantic Ocean observations by focusing on research and innovation activities aimed at deploying an Integrated Atlantic Ocean Observing System (IAOOS), building on existing capacities on both sides of the Atlantic.

The proposals related to the IAOOS initiative have been encouraged to cover the whole Atlantic with the objective of delivering the knowledge platform supporting the understanding of the ocean processes at the level of the entire basin. This call has been definitively linked to the Galway statement and to the Trans-Atlantic Cooperation with the USA, Canada and Russia.

Scientific Topics in need of new Horizon 2020 Calls in Polar areas

As already mentioned, the 2014-2015 Working Programme of Horizon 2020 has not explicitly considered polar research in any of its calls, beside two notable exceptions that are the Call Blue Growth-15, European Polar Research Cooperation, within the Societal Challenge pillar and the Call INFRASUPP-6-2014, within the Excellent Science pillar.

In particular, call BG15 is supporting a planning and coordination effort to develop a consistent, comprehensive strategy to develop progressive European and international cooperation research in the polar areas and in the Atlantic areas related to them. This effort will result in new calls that will meet the scientific priorities highlighted in Chapters 2 and 3 of this volume, that have not so far found any support in the 2014-15 Work Programme.

In this regard, it should be once more emphasised that the scientific priorities discussed in Chapters 2 and 3 could have been potentially related to different calls, as shown in Chapter 4 in relation to global change in the oceans, their effects on ecosystems, biodiversity, adaptation, ecosystem services, etc., which, however, do not refer explicitly to the polar areas. However, polar research provides a fundamental contribution to the understanding of issues related to changes in the environment and ecosystems due to current global changes; the missing of specific polar calls in the Work Programme 2014-15 raises a serious gap in understanding the environmental changes and the related effects of ecosystems at a global scale that must necessarily be filled by the results and developments of Call BG15 and of the infrastructure calls.

The forthcoming Horizon 2020 Calls and the Work Programmes 2016-2017

Recent communications, made available both via web platforms and through presentations at specific conferences and meetings, indicate that the European Commission will put special focus in the forthcoming calls on facilitating a new boost for jobs, growth and investment, involving in particular the young generations.

The Draft Horizon 2020 Work Programme 2016-2017 clearly indicates such focus, which should lead to improving Europe's global competitiveness. On the basis of a broad consultation several key priorities have been assumed as guidelines for the forthcoming Work Plan 2016-2017.

As shown in the draft documents, the currently available key priorities for 2016-2017 should be:

- A new boost for jobs, growth and investment
- A connected digital single market
- A resilient energy union with a forward-looking climate change policy
- A deeper and fairer internal market with a strengthened industrial base
- A stronger global actor, towards a new policy of migration and an area of justice and fundamental rights on mutual trust.

At the time of production of this manuscript the Draft Horizon 2020 Strategic Plan for the development of the Work Programme 2016-2017 is still undergoing the finalisation process.

Research infrastructure as well as a number of cross-cutting features that are expected to be embedded across the whole new Work Programme: among them, 'Innovation', 'International Cooperation' and 'Climate Action'.

Making reference to the Horizon 2020 Pillar 'Excellent Science', the Research Infrastructure area is expected to be again supported under the condition of funding sustainability, links with industry, transnational access and open access to data. Five specific calls should be expected under the Infrastructures area, two of which should be also relevant to the polar science priorities of Chapters 2 and 3. The first call should provide support to existing facilities identified under the ESFRI roadmap, but with a "new emphasis on long-term sustainability and efficient operation". The second call addresses the integration of infrastructures, the innovation output, and promotes the wider access of users, particularly in developing Countries.

In the specific framework of polar infrastructures, in the 2010 European Polar Board Strategic Position Paper *European Research in the Polar Regions: relevance, strategic context and setting future directions in the European Research Area* (already mentioned in Chapter 1 of this volume) the European Polar Board highlighted some of the priority needs for sharing the use of scientific infrastructures, synchronising planning and opening access to infrastructures and data. These needs could be well aligned with the targets of the next

Figure 4.7. Emperor Penguins on the sea ice in front of RRS James Clark Ross. Taken during the JR240 ICEBell Cruise in the Weddell Sea
© Pete Bucktrout, British Antarctic Survey

Infrastructure Calls of Horizon 2020. As an example, the Arctic Research Icebreaker, Consortium for Europe proposal (ARICE) should be mentioned, which aims at creating a mechanism for improving the coordination and a more cost-effective usage of available European heavy research icebreakers. The proposal has been positively evaluated by the EC for future Integrating Infrastructure Initiatives (I3) in Horizon 2020.

Other areas of special interest for the Commission should be linked to resilient energy, climate change and sustainable development, strengthening of links between research and industry and social welfare.

Making reference to the Pillar Societal Challenges (SC2), two expected areas should be primarily considered as relevant to the priorities listed in Chapters 2 and 3: *'Food security, sustainable agriculture and forestry, marine and maritime and inland water research and the bioeconomy' (SC2)*, and *'Climate action, resources and raw materials' (SC5)*.

Within SC5, a call addressing, among others topics, climate services, vulnerability and earth observations that may be relevant for polar science priorities might be expected. Special attention is expected to be devoted to tools, products and services to mitigate the effects of climate change and protect vulnerable areas, including coastal regions.

In the 2014-2015 calls, the focus area, Blue Growth, has targeted four main areas:

- Sustainable exploitation of the diversity of marine life
- New offshore challenges
- Ocean observation systems/technologies
- Horizontal activities for innovation, communication and society's engagement.

The Scoping Paper for Food Security, Sustainable Agriculture and Forestry, Marine, Maritime and Inland Water Research and the Bioeconomy recently posted on the Horizon 2020 website indicates an orientation towards a new form of exploitation of the oceans, seas and coasts could contribute to tackling the scarcity and vulnerability of strategic resources, and provide technological, industrial and recreational opportunities. The expected Blue Growth Call should provide funding for the development and piloting of ocean floating platforms for energy and food production, large-scale algae biomass refineries, and deep sea mining. It should also tackle the problem of marine pollution, and support projects on ocean monitoring and observation.

In this context the need for integrating and enhancing a robust system capable of delivering accurate information on the status and the potentialities of the oceans to the relevant stakeholders is highlighted.

The development of tools to monitor, understand and predict ocean and climate change processes, ranging from marine observations from the coast to the open ocean and from the surface to the deep sea, joint to the promotion of partnerships for funding and sharing of data, are indicated as key components for achieving the target.

In addition, the document indicates that transdisciplinary research and innovation generating synergies among the various blue economy activities, and the increase of societal acceptance, will be critical to achieve a productive, healthy and sustainable maritime economy for society.

If the indications of the scoping paper are confirmed, marine sciences experts might find new opportunities of funding and cooperation in the areas of ocean and climate change processes, protection and cleaning of the oceans, reduction of pollution as well as analysis of the status of marine biodiversity as linked to food production and sustainable development.

When focusing on polar areas, this call should accord well with the recommendation of the European Marine Board, which produced a commentary in 2013 concurring with what was already highlighted in 2010 by the European Polar Board: "Getting ready for an ice-free Arctic". The sentence underlined that a major increase in the capacity of observing and studying the Arctic Ocean ecosystem is urgently required before the region is transformed by rapid environmental changes and commercial exploitation.

The commentary highlighted the need to establish a comprehensive and sustainable marine observation and data-exchange system, covering the full extent of the Arctic Ocean.

The BG-15 Call, and the related EU-PolarNet project funded in the framework of the Work Programme 2014-2015, should result in a comprehensive European polar research programme, setting up a continuous stakeholder dialogue and communicating user needs to the appropriate scientific community and/or research programme managers. The EC may look at this project as a source of information and guidelines for upcoming themes for calls within Excellent Science and Societal Challenges, which could deal with the following scientific domains:

- Integrated Arctic Observing System (2016)
- Impact of Arctic change on the climate and weather of the Northern Hemisphere (2016)
- Climate impacts on Arctic ecosystems, resources, new economic activities (2017)
- 1.5 million year Earth observation system for improving climate prediction (2016)

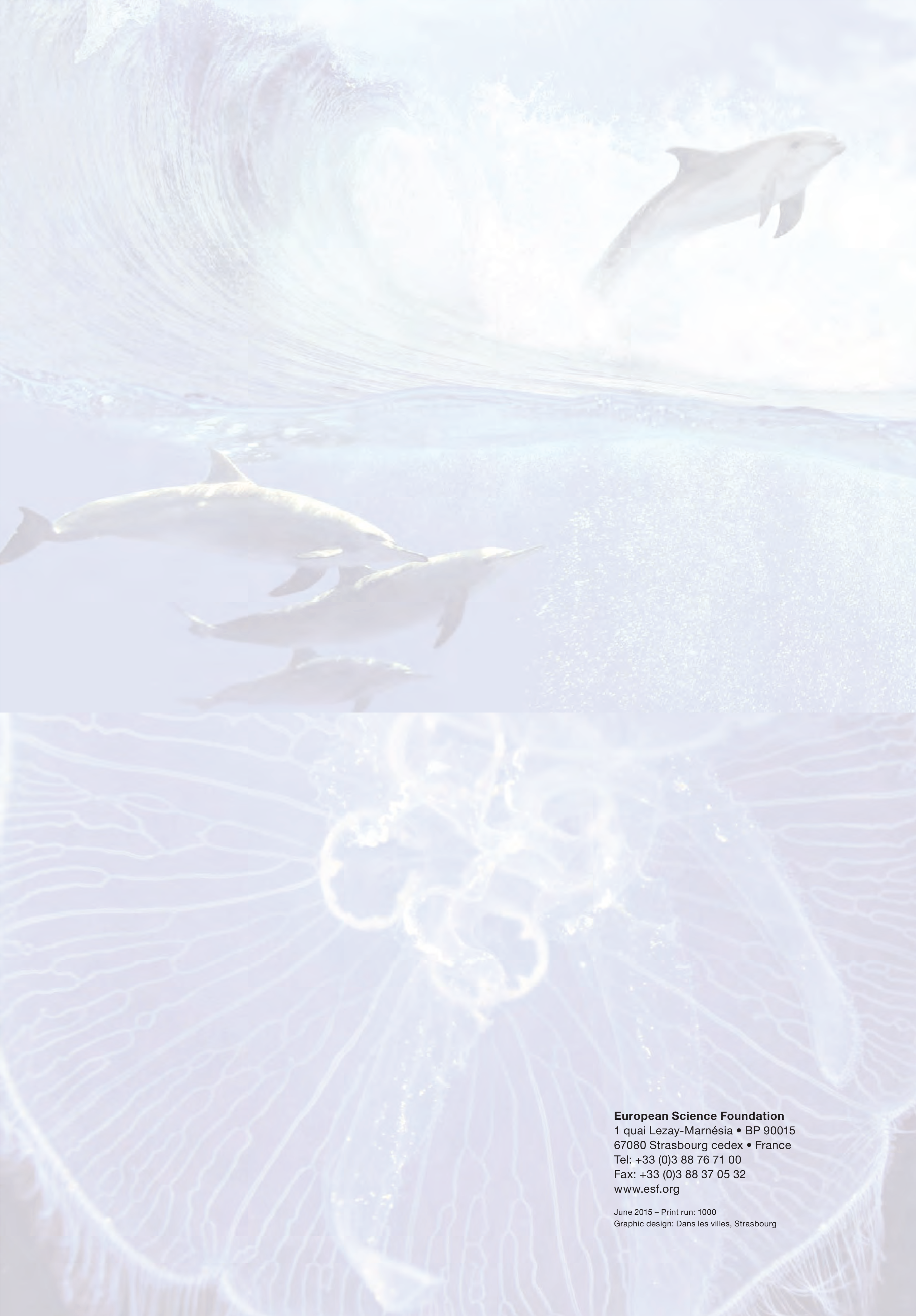
The Call 'Climate action, resources and raw materials' is expected to address, among other topics, climate services, vulnerability and earth observations that may be relevant for some of the priorities listed under Chapters 2 and 3. Special attention is expected to be devoted to tools, products and services to mitigate the effects of climate change and protect vulnerable areas, including coastal regions.

The development of the contents of the forthcoming Work Programme 2016-2017 has been further discussed by the Horizon 2020 Advisory Groups within the first half of 2015. Next, the member states will be requested to express their opinion on the configurations of the Programme. A final decision is expected at the beginning of summer and the adoption of the Work Programme will consequently be expected in the third quarter of 2015. This schedule might still offer some possibility of integrating at least some of the highlighted marine and polar science needs into the forthcoming Work Programmes. This, of course, will require proactive action by the relevant stakeholders.

As a general consideration, in the framework of the forthcoming 2016-2017 Calls offering potential areas of development for the priorities listed under Chapters 2 and 3, it would be advisable to develop a well-balanced distribution of funding among proposals addressing the status of the oceans at every latitude, including biodiversity, in light of present and past climate changes and proposals addressing the responsible and sustainable exploitation of the ocean resources.

This approach would ensure harmonised progress in the understanding of the delicate functioning of the oceans and biodiversity in temperate and Polar regions and in addressing the need for sustainable development of society.

In the current context of global change, sustainable and responsible exploitation of the oceans can be realised only through a deep understanding of the ocean processes and of the associated ecosystems spanning every latitude of Planet Earth.



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June 2015 – Print run: 1000
Graphic design: Dans les villes, Strasbourg