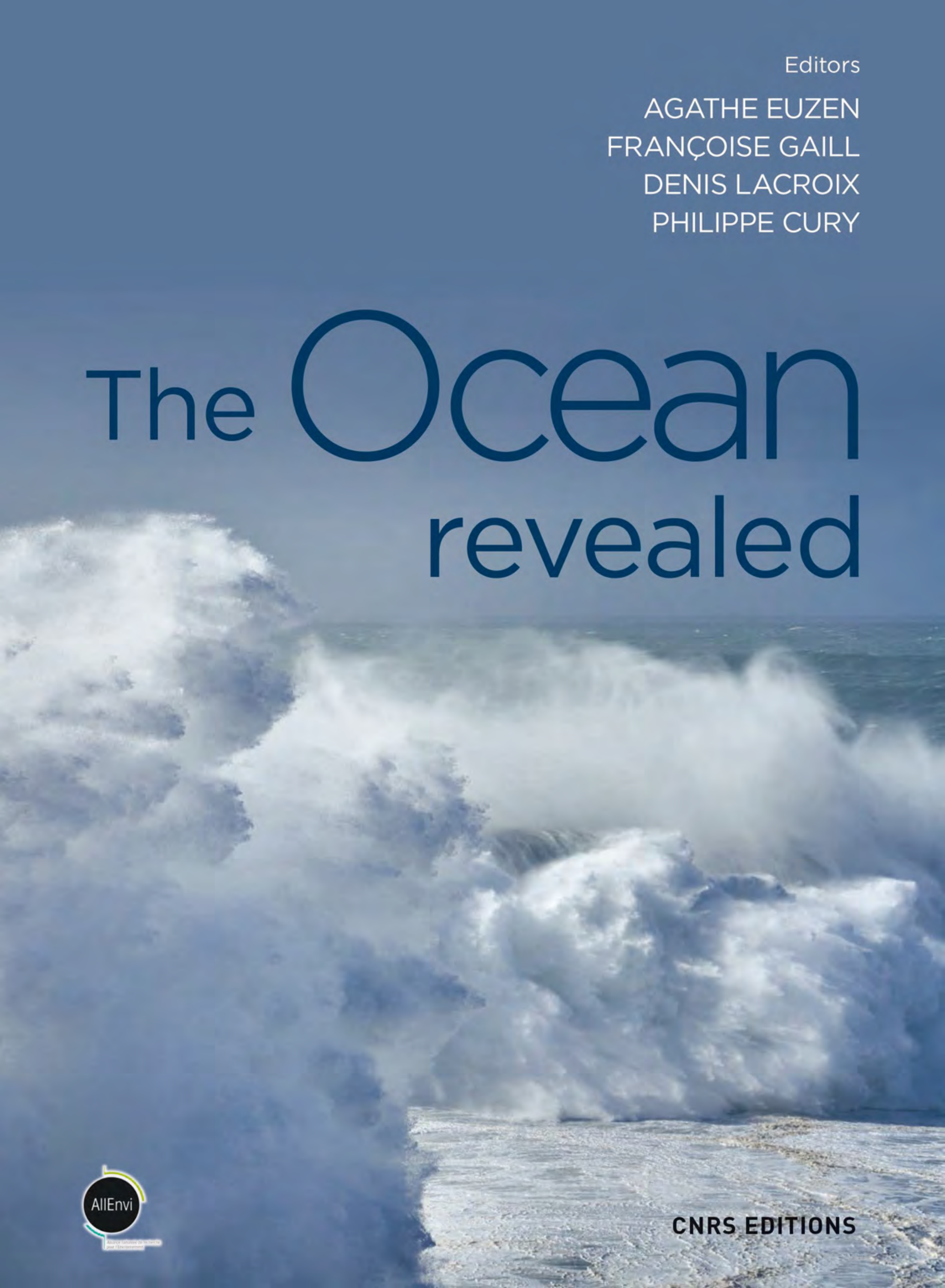

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The Ocean revealed

AllEnvi

CNRS EDITIONS

The Ocean

revealed

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Contents

- Part One -

THE OCEAN: KEY CHALLENGES

- Part Two -

WHAT IS THE OCEAN?

- Part Three -

EXPLORING THE OCEAN

- Part Four -

HISTORY AND REPRESENTATIONS OF THE OCEAN

- Part Five -

USES OF THE OCEAN

- Part Six -

The risks

- Part Seven -

THE GOVERNANCE OF THE OCEAN

- Part Eight -

THE OCEAN: WHAT LIES AHEAD?

- Part Nine -

ANNEXES

Preface

Serge Ségura

Ambassador for the Oceans

A huge amount of work and knowledge has gone into this book, 'The Ocean Revealed', produced by AllEnvi, the French environmental research alliance. Cast your eye over the table of contents and you will see the wide variety of topics covered, from the ocean in paintings to deep-sea mineral resources, from the ocean's blue colour to sea birds.

This holistic approach is now essential in every discipline. For anyone dealing with the ocean, it is the only way to produce a complete and consistent result. It is no longer possible to focus on a single area of expertise. Today, two things are urgent. First, we need to help the ocean heal the wounds that human society has inflicted upon it, while we still have time. Secondly, we need to find a sustainable way of using all the ocean has to offer in terms of resources, communication and leisure.

The world's leaders are also increasingly adopting this approach to the ocean. The ocean is now more than a mere backdrop for State events. Previously, only the event mattered, the setting could be neglected. That is no longer the case. Maritime spaces have become a focus in international relations, a matter of power, might, resources and also of responsibility, development, cooperation and peace.

This book shows the array of scientific disciplines that take the ocean as their subject. The role of science is vital in understanding the ocean. Apart from in the minds of a handful of regressive and obtuse politicians and leaders, the need for protection is no longer in doubt today, but conservation efforts can only be effective if we have in-depth knowledge of what needs protecting: science is thus fundamental. Scientists from every discipline face a heavy burden of responsibility and they will have to broaden their view of marine and maritime issues beyond their own field to build knowledge and then put forward solutions for protection and sustainable use. It is wonderful to see that an increasing number of scientists are taking this on-board. It has a positive impact on the States' capacities to put forward proposals during international discussions on the ocean, covering Sustainable Development Goal 14, for example, or the conservation and sustainable use of high sea biodiversity.

This book is a timely resource that will inform a broad audience, not only decision-makers but anyone with a love of the ocean. Every one of us has a role to play and the people behind this book should be thanked for sharing their extensive knowledge, a valuable resource that will help us to forge our own view of the ocean while opening up new avenues for reflection.

Foreword

François Jacq[1], Jean-Paul Moatti[2] and Stéphanie Thiébault[3]

Following 2015's 60 research success stories for a sustainable planet (*60 succès de la recherche pour une planète durable*), coinciding with COP21, then COP22 and the publication of The Mediterranean Region under Climate Change – La Méditerranée face au changement climatique, an overview of the latest scientific results on the subject, researchers from the French Research Alliance for the Environment's organizations (AllEnvi) are now working hard in the run-up to the Our Ocean conference (Malta, October 2017).

The ocean may be seen as the driving force of life on Earth. It covers more than 70% of the planet's surface, regulates the Earth's climate and is home to a high proportion of the currently uncharted biosphere. The ocean serves as a carbon pump and produces oxygen, and it and the organisms that it harbours play a predominant role in climate regulation. However, it is increasingly affected by global changes and the health of the ocean has become a crucial issue for our world's climate. Our aim with this publication is to raise our readers' awareness of all the importance of all this.

The ocean stores heat from the sun and transports it from the tropics to more temperate regions then to higher latitudes, *via* the ocean currents created by prevailing winds. Conversely, the cold waters of the polar regions move through the ocean's depths towards the tropics. The ocean is able to store more heat than the land masses and a thousand times more than the atmosphere. In the present day, human activity increases greenhouse gas emissions and the ocean is getting warmer. Since the start of the Industrial Revolution (1800–1850), a third of all carbon dioxide linked to human activity has been absorbed by the ocean, which thus helps mitigate global warning. In fact, 90% of the excess heat from human activity has been absorbed, but this heat absorption has caused the ocean's temperature to rise to a depth of at least 700 m. The increase reaches the ocean floor in the polar regions and is spread to all ocean basins.

Another impact of global change is ocean acidification, which may lead to CO_2 saturation and, if the ocean's capacity for absorption is lost, the quantity of CO_2 in the atmosphere would rise. The ensuing consequences for the climate would be much more severe than the current observations and forecasts.

When CO_2 comes into contact with sea water, some of it is dissolved in the form of carbonic acid and this acidification alters all the chemical balances. Its consequences have been studied since the late 1990s but are not yet fully understood but we do know that certain phytoplankton algae or animals with calcareous skeletons (such as corals) experience anomalies when they develop in a more acidic environment.

The greater the rise in the ocean's surface temperature, the more sea water evaporates. The water vapour contained in the atmosphere increases, speeding up and significantly increasing the formation of meteorological phenomena and, as a result, the frequency of storms. The development of extreme phenomena is also a risk for the coming years: destructive events such as hurricanes and typhoons could become more violent as they draw their energy from the sea's warmth which, as we have seen, is rising.

As it gets warmer, the ocean dilates because, at an equal quantity, hot water has a greater volume than cold water. The melting of the polar ice sheets and glaciers accounts for at least 50% of rising sea levels. Researchers estimate that the sea level has already increased by an average 3 mm a year since 1992 and this trend is accelerating. Rising sea levels across the globe have visible consequences such as the submergence of delta zones, the salinization of lowlands and erosion of the coastline.

The ocean is home to millions of species. Climate change also affects marine biodiversity, crucial to the health of the oceans and the planet. It modifies the composition and

Free Ocean 2016. Oil on Paper. Triptych. 76 x 168 cm. © T. LAMAZOU. ■

distribution of species able to thrive in the ocean, *i.e.* able to feed, grow and reproduce there, and impacts relationships between species.

While certain marine species adapt to changing temperatures, others move towards the poles or migrate to other areas (tropical fish are now found in the Mediterranean, for example). Some species have become extinct (certain corals suffer bleaching and mortality).

Water acidification caused by higher CO_2 levels in the oceans directly impacts marine organisms with a calciferous skeleton or shell (phytoplankton, crustaceans, molluscs, corals…) leading, for example, to considerable shrinking.

Exceptional climate events weaken natural habitats (through erosion, flooding…) and alter conditions for marine life along the coastal strip and lowlands, especially in mangrove and grassy habitats where species often reproduce and which are important sources of food for many fish post-larvae and juveniles.

In addition to the effects of human activities such as overfishing and pollution, climate change has an impact on food resources for human populations. Fish is actually the leading source of animal protein for a billion people.

This biodiversity loss also means a loss of 'genes' and valuable molecules for medical and industrial research, the wealth and diversity of which remains largely uncharted to date.

The threats to oceans are predominantly felt in intertropical and Mediterranean areas where the human communities that are most dependent on marine resources are concentrated, along with the highest number of zones identified as especially vulnerable to climate change. This change is even threatening the very existence of some developing island states. Hence, from among the 17 Sustainable Development Goals (SDG), adopted by the United Nations in 2015 and to be achieved by 2030, SDG 14, which aims to 'conserve and sustainably use the oceans, seas and marine resources', will have positive repercussions on all the other goals, most notably eradicating poverty and hunger in the world (SDG 1 and 2), improving health (SDG 3) and reducing inequalities 'within and among countries' (SDG 10).

The aim of our publication is thus to draw the attention of as many people as possible to the threats now endangering the ocean and its crucial role in the survival of living organisms, including the human race.

With this book, AllEnvi not only takes stock of high-level French scientific research on the oceans, encompassing various disciplines, but also highlights the importance of scientists' contributions to the UN negotiating mechanisms, from climate conferences (United Nations Framework Convention on Climate Change UNFCCC) and the biodiversity conference to the SDGs.

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- Part One -

The ocean: key challenges

Previous page:

Penguin colony in Cape Town, South Africa. © G. WEEKS. ■

1. What is at stake

Laurent Bopp, Marina Lévy and Pierre-Yves Le Traon

Planet Earth is an ocean planet. We can hardly ignore the fact that the ocean covers almost two thirds of our planet. Since the dawn of time, humankind has had an ambivalent relationship with the immensity and hostility of this very specific environment. However, the ocean holds a strong attraction for human societies, with nearly 40% of the world's population living less than 100 km from the coast and most of the world's big cities built on the edge of the ocean.

However, the connection between humankind and the ocean runs much deeper than simple geographic closeness. The ocean plays a crucial role in the climate of our planet. It exchanges significant quantities of energy and water with the atmosphere. It distributes energy from the tropics to higher latitudes, warming the polar regions and cooling the tropics. It also helps define the characteristics of regional climates by influencing air temperature and rainfall amounts.

The ocean is also a vast reservoir of biodiversity. Indeed, it was in this environment that life first appeared on Earth around 4 million years ago. Today, nearly 230,000 marine species have been recorded and there are probably more than a million more to discover! Technological breakthroughs, such as metagenomics, are considerably speeding up the identification of new species.

View of New York. CC0 1.0. ■

The ocean is a vital factor in a myriad of human activities, as it harbours vast food, energy, mineral, genetic and other resources. Fishing provides almost 20% of animal proteins consumed by the world's population, with nearly 100 million metric tons of fish and other seafood products taken from the sea every year. Energy resources found at sea include offshore hydrocarbons, already intensively exploited, and renewable energies, which are now experiencing strong growth and offer potential that humankind can no longer do without. Polymetallic nodules, manganese crusts and hydrothermal sulphides found in the depths of the ocean are potential sources of minerals. These resources may be difficult to access but they could help diversify mineral supply sources, which are currently under acute pressure. Finally, genes and molecules of marine origin are now being used in the medical and pharmaceutical sector. Again, there is huge potential, even for other sectors such as biofuels, cosmetics and food.

Activities connected with the ocean play an important role in the world economy and the 'blue economy' sector accounts for 2.5% – $1,500 billion – of global gross value added.

Nevertheless, the ocean changes, undergoing transformation as it reacts to human disturbances of every kind, including climate change, acidification, pollution, exploitation and overexploitation of an array of resources. In light of these changes and the key role it plays for many human societies and activities, the ocean is central to sustainable development issues. As such, several United Nations Sustainable Development Goals concern the ocean: first and foremost, Goal 14 (SDG14), which refers to sustainable use of the ocean, but also SDG2 which covers food security, SDG7 on clean and sustainable energy, and SDG13 on how to tackle climate change.

2. A blue planet

Catherine Jeandel and Pascale Delecluse

What if the Earth were called ‘the Sea’? Looking closely (or from afar), this little pun doesn’t seem so far-fetched. After all, what do astronauts see when they are orbiting in space? A very blue planet! Blue because of its oceans, which cover almost three quarters of its surface. Rather than being called ‘the Sea’ it is therefore nicknamed the ‘blue planet’.

Into the marine world

For us, here on land, the ocean is another dimension, but a few figures can give us an idea of its size. It has an average depth of 3800 m, but it can be as much as 11,020 m deep in the Mariana Trench. This means that Earth’s chasms are deeper than its peaks are high, with Mount Everest standing at 8848 m. The ocean also represents a huge volume of salt water: 1.4 billion billion cubic metres! Its average temperature is just 2 °C, because the sun only heats a thin layer of water on the surface. The coldest temperatures are negative, because the salt in seawater means that it does not freeze until it reaches –1.9 °C. Concerning this salinity, seawater contains 35 g of salt per litre on average, which means that the evaporation of 10 litres of seawater leaves a small 350 g cup of salt, as seen in the ancestral technique of salt evaporation ponds (cf. IV.8). This salinity varies only slightly between different parts of the world, but the slight variations are crucial for characterizing water masses.

The ballet of the currents

Just as upper-air winds bring us warm or cold air masses, marine currents transport warm or cold water masses. These differ in their temperature and salt content: two defining parameters for their density. Cold water will be denser than warm water, and salty water will be denser than less salty water. In the Atlantic, off the European coasts, there are warm and relatively salty surface waters, intermediate waters (800-1000 m) coming from the Antarctic which are cold but with low salinity, and at the same depths, oceanographers have also observed patches of warmer but much saltier water coming from the Mediterranean, *via* Gibraltar. Further below is a layer of cold water, which is relatively salty and about 2 km thick, coming from the North Atlantic. Right at the bottom is the coldest and densest water, which comes up from the Antarctic. This ballet of water masses, a sort of marine layer cake, is driven by the currents. For example, the Gulf Stream, which forms in the Gulf of Mexico, comes out to the south of Florida, moves up northwards and leaves the American coasts to cross the Atlantic, towards the English and Norwegian coasts (cf. II.11). It flows to the surface, carrying waters that are relatively warm, considering their origin. These waters cool near to the Arctic Circle, where they become dense and sink towards the depths, then move back of towards the south, along the American coasts at a depth of 1.5 to 3 km. At Cape Horn, the waters change course towards the east and flow around the Antarctic, then into the Indian and Pacific oceans. They resurface *via* Drake’s Passage and the Straits of Indonesia, then move back up the Atlantic, and the cycle starts again. On average, the water takes 1000 years to complete one full lap. To give an idea of the scale of these movements, the current circling the Antarctic (the Antarctic Circumpolar Current) equates to around 140 times and the Gulf Stream to 80 times the transport of all the world’s rivers combined.

Fig. 1 – **Satellite photograph of Earth, illustrating why it is nicknamed the ‘Blue Planet’.** Source: NASA. ■

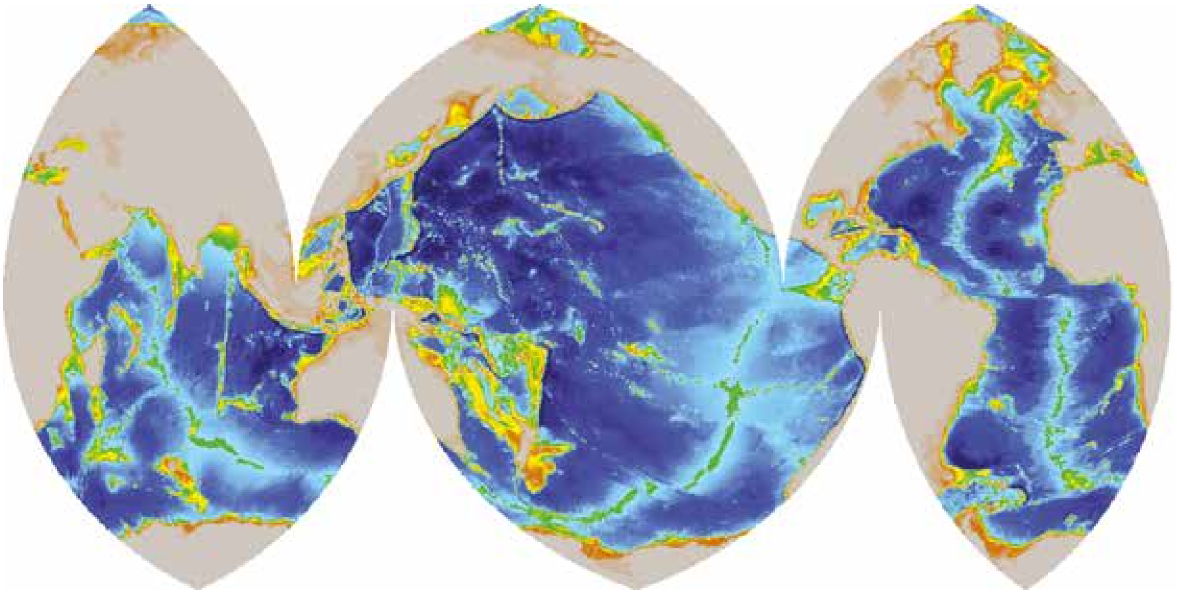

Fig. 2 – **Bathymetric map of the world's oceans.** Source: LSCE. ■

To describe these gigantic flows with manipulable figures, oceanographers use a unit called the Sverdrup (Sv). One Sv represents one million m^3 of water per second: the sum of all the rivers in the world therefore equates to 1 Sv.

This gigantic conveyor belt allows heat and water to be exchanged between the ocean and the atmosphere, between the lowest and highest latitudes. These exchanges shape our current climate, which has been stable for around 8000 to 10,000 years, since the end of the last ice age. The ocean is therefore an essential regulator of the Earth's climate (cf. I.14).

The ocean as a place of life

This salty expanse of water is also a place of life. Like the grass and the trees, which take mineral salts from the earth and use sunlight to grow (using photosynthesis), algae and phytoplankton absorb dissolved nutrients from the water to start a chain of life, becoming food for grazing zooplankton. This itself is eaten by fish, which are a food resource for humans. Through this chain, life transforms dissolved carbon into solid matter. This oceanic carbon is in contact with carbon in the atmosphere, where it is found in the form of carbon dioxide: CO_2. The CO_2 dissolves at the air-sea interface, especially in the coldest waters: this is the physico-chemical pump. The matter formed at the surface by biological organisms sequesters this carbon in the seabed, when these organisms die and sink to become marine sediments: this is the biological pump. Thus, the ocean also plays a role in regulating carbon dioxide in the atmosphere. Without these mechanisms of life and sequestration, the concentration of CO_2 in the atmosphere would be double what it is today. As the concentration of CO_2 and the Earth's climate are closely connected, this mechanism also makes the ocean a climate regulator. The natural flows of carbon dioxide exchanged between the atmosphere and the ocean are in the region of 90 gigatonnes per year.

Imbalance

On average, human activities emit 10 gigatonnes of CO_2 per year. A third of this additional gas penetrates into the ocean, is absorbed in the surface layers and therefore upsets the natural balances. Moreover, 40% of this excess carbon dioxide remains in the atmosphere, aggravating the greenhouse effect and therefore contributing to global warming. Two balances are affected: the physico-chemical and biological CO_2 pump, and the energy exchange between the air and the water, since the ocean absorbs 90% of global warming. Climatologists are therefore fully justified in worrying about this slow accumulation of changes in our 'blue planet'.

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3. The ocean, a key component in the climate system

Laurent Bopp and Marina Lévy

How exactly does the ocean affect the climate system? Whenever we think 'climate', we almost systematically think of the atmosphere, air temperature, the amount of precipitation, extreme events, storms, drought and so on. 'Climate' is defined as the statistical distribution of the meteorological conditions of the Earth's atmosphere in a given region and over a certain length of time. The ocean is not included in this definition yet it exerts a considerable influence on meteorological conditions and their evolution over time. Our planet's climate system cannot therefore be fully understood without looking at how the ocean works.

The ocean, a reservoir of heat and carbon

The ocean is a large heat reservoir – much larger, in fact, than that formed by the atmosphere. Firstly, it has a much greater mass than the atmosphere: at 1.4 1021 kg compared to 5.2 10^{18} kg, it is almost 300 times greater. Secondly, the specific heat capacity of sea water is also greater than that of air: when compared to a kilogram of air, it takes four times more energy to warm a kilogram of seawater by one degree. In all, the quantity of energy stored by the ocean warmed by one degree is 1,200 times greater than if the atmosphere is warmed by one degree.

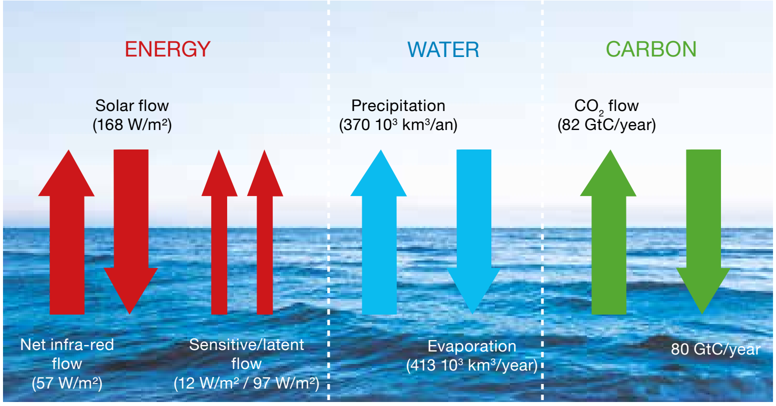
However, because of all this, the ocean has considerable thermal inertia, which produces the characteristics of 'oceanic' climates that are milder in winter when the ocean returns the heat stored during summer to the atmosphere, and that have more moderate temperatures in summer when the ocean absorbs a significant portion of the sun's incidental radiative energy. The ocean also plays a key role in heat transfer between high and low altitudes. General ocean circulation, combined with net energy absorption in tropical latitudes sees the ocean redistribute some of this energy towards the atmosphere in higher altitudes, thus limiting thermal contrasts between the Equator and the poles (cf.II.11).

A second fundamental factor: the ocean is a vast carbon sink. It contains close to 40,000 billion tons of carbon, mainly in the form of bicarbonate ions, HCO_3^-, dissolved in sea water. This is almost 50 times the volume of the atmospheric carbon sink, where the carbon is found in the form of carbon dioxide or CO_2. The ocean's high capacity to store carbon is linked to carbonate chemistry and the basic pH of seawater: once dissolved in seawater, CO_2 combines with water molecules to give bicarbonate and carbonate ions. There are considerable carbon exchanges between the atmosphere and the ocean, which largely regulate the atmospheric concentration of CO_2, one of the main greenhouse gases.

The ocean, a time-delay effect on climate change

The significance of the ocean in the climate system is illustrated by its key role in climate change in recent decades. It acted and continues to act as a time-delay device with regard to this change. Using seawater temperature measurements collected since the 1950s *via* ships, then a worldwide network of profiling floats (the ARGO network, cf. III.3), oceanographers have demonstrated that the ocean has warmed significantly in its first 2,000 metres depth. Surface waters have already warmed by an average 1°C and another one-degree increase is feared over the coming decades. The ocean has thus absorbed the largest portion of the extra heat in the climate system (more than 90% since the 1970s). The ocean therefore limits the speed at which the atmosphere warms up.

The ocean is a substantial carbon sink: it absorbs several billion tons of carbon every year (cf II.14). It has captured nearly 30% of anthropogenic carbon emissions since the start of the industrial age, thus helping to reduce CO$_2$ concentrations in the atmosphere significantly.



Considerable flows of energy, water and carbon are exchanged between the atmosphere and the ocean every year. The ocean transports the energy, water and carbon *via* ocean currents. Energy, for example, is carried from low to high latitudes, which helps redistribute energy between the Equator and the poles. Photo © Jannoon028 / Freepik. ■

Threats to the functioning of the ocean system

Nonetheless, the moderation of anthropogenic climate change by the ocean has ramifications on the latter: as it absorbs heat, the ocean warms up and as it absorbs carbon, it becomes more acidic (cf. II.9). Other major modifications occur concurrently with or result from these changes. The summer Arctic ice cap is disappearing (cf. VIII.12) and the sea level rises because the ocean accumulates almost all the water from the melting of glaciers and ice sheets (cf. II.15), but also because the ocean dilates as it is heated. The increase of heat content in the ocean also affects its exchanges with the atmosphere, especially the exchange of heat and water vapour, and the global hydrological cycle is intensified. These variations also disrupt the main marine currents, because the temperature, precipitations and winds that drive the currents are altered. These changes to the ocean's fundamental physical and chemical properties impact ecosystem functioning and marine species, by modifying their geographic distribution and their seasonal rhythms (cf. VI.7).

Humans and some of their activities come at the end of the 'impact chain'. Hence, the ocean supplies 11% of animal protein consumed by humans in the world and is therefore a crucial factor in food security for hundreds of millions of people.

A sleeping giant?

However, although the ocean may be seen as a gentle giant, slowing down anthropogenic climate change, the modifications it undergoes may have a subsequent effect on climate change itself, causing it to increase or decrease on a global or regional scale. How? Firstly, because some marine currents, especially the deep currents that carry considerable quantities of water and play a fundamental role in the climate system, are disrupted and may no longer play their part in the transfer of energy from the Equator to the poles. Secondly, because physical, chemical and biological changes to the ocean may reduce its capacity to continue to absorb anthropogenic carbon emissions.

The study of the repercussions of variations in ocean circulation on the climate, and the interactions between climate change and the ocean's carbon cycle are two very active areas of research at present. More intense observation programmes, new technological breakthroughs and digital modelling should pave the way for considerable progress in knowledge of the links between ocean and climate.

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4. What are the challenges for biodiversity?

David Mouillot

Over the last two years (2015 and 2016), there have been at least four major events concerning the oceans: *i)* following the expedition of the schooner *Tara*, which gathered 35,000 plankton samples, scientists showed that over a third of the microorganisms collected and 99% of the viral genomes were unknown (cf. III.6), *ii)* the massive extent of the coral bleaching following an El Niño episode was unprecedented in history, with almost 93% of Australia's Great Barrier Reef affected, *iii)* President Obama created the world's largest no-take marine reserve (Papahānaumokuākea in Hawaii), over a surface of 1.51 million square kilometres, or three times the area of France, *iv)* conflicts and demands multiplied, regarding claims on the resources of isolated islands, for example Tromelin (Indian Ocean) or Clipperton (Pacific Ocean) for France. These four major events are clear manifestations of some issues faced by marine biodiversity. Firstly, our lack of knowledge about species and their biogeography is a main challenge for new technologies and future expeditions. Secondly, the extreme vulnerability of marine biodiversity to global changes requires unprecedented conservation efforts. Finally, human demography and the growing needs of our societies are driving nations and populations to overexploit their natural resources, and even extend their efforts beyond their borders.

Identification and biogeographic challenges

91% of eukaryotic species in the oceans are still unknown, despite 250 years of sampling and taxonomic classifications. In 2015, of the multicellular organisms (plants and animals), 230,000 species were identified in the oceans (across all habitats). Almost a third of these (70,000 species) live on coral reefs, which boast the richest species diversity of all the Earth's ecosystems, and where there are still an estimated million new species to discover (cf. II.25).

Thanks to a first technological revolution, metagenomics, we can now accelerate the identification of new species. This means that the encyclopaedia of life, including in the oceans, could be completed within a few decades, for multicellular organisms. The main obstacle lies not in sequencing new organisms, but rather in accessing still unexplored habitats, such as deep-sea ecosystems or the most isolated seamounts.

The XL Catlin Seaview SVII camera in action, in the Maldives in 2015. It allows the collection of 360° images every 3 seconds, travelling at a speed of 4 km/h. © The Ocean Agency / XL Catlin Seaview Survey / C. BAILHACHE. ■

As well as identifying species, science also needs to know their geographical distribution and abundance, since protection statuses like those of the International Union for Conservation of Nature (IUCN) are based on this knowledge. In this domain, two revolutionary techniques are being developed, which will allow us to overcome this information deficit. These are environmental DNA and automated image analysis. The first technique allows us to detect DNA fragments left in the water by passing organisms. The second allows us to harness the increased provision of videos and photographs, to automatically recognize species using increasingly powerful algorithms (deep learning). For example, the Catlin Seaview Survey (Fig.) has already allowed over 1000 km of reefs to be covered across 26 countries since 2014. This is the equivalent of the combined efforts of all the visual underwater dive surveys over the last 40 years.

The rise of remotely operated underwater vehicles, aerial drones, then high-resolution satellite images (< 10 cm) will only strengthen this automated monitoring of marine biodiversity in the digital era.

Conservation challenges

The protection of the oceans, their habitats and their species has never been so popular, with unprecedented efforts to create ever-larger Marine Protected Areas (MPAs) (cf. VII.11). Yet these efforts are still not enough to achieve the objective of 10% coverage of the oceans by 2020 (COP 10): we have still only reached 7%. The global trends and this positive dynamic hide a much more mixed truth and major new challenges for biodiversity.

Firstly, the concept of an MPA remains vague, and encapsulates many regulations and legislative measures. In reality, only 6% of MPAs have 'no-take' status, guaranteeing that all fishing activities are forbidden. The others do not fulfil their mission to protect exploited species. Secondly, these MPAs are not distributed in an optimal and balanced way between the different oceans, with a deficit for most countries in the Global South and a strong tendency to promote the creation of new MPAs (particularly large ones) far from human activities, to avoid conflicts. In these cases, the expected benefits remain marginal, because nations and managers favour easy protection and the low-cost achievement of coverage objectives, to the detriment of real effectiveness. On top of this, IUCN statuses are very poorly informed for most species, particularly marine species (only 3%), so the prioritization of new marine areas to be protected is still based on very incomplete information. Finally, protection is far from sufficient where fishing is concerned, in the face of the many threats (particularly climate threats) that exist. For example, the reduction of fishing has failed to prevent the exceptional bleaching episodes that have affected the Great Barrier Reef since 2015. These ocean heat waves, like the pH drop due to increased CO_2 levels in the atmosphere (cf. II.9), demand a response which goes well beyond local protection of the most vulnerable ecosystems and their species. Globally, the magnitude and speed of the changes observed over recent decades have known no equivalent in the last 20 million years (a 0.1 unit pH decrease, for example). They threaten the calcified habitats where most of marine biodiversity resides, and highlight the need for global action in addition to local protection.

The challenge of reconciling conservation and exploitation

Protecting the oceans, particularly through the creation of no-take MPAs, remains a difficult option to implement on a very large scale, especially where marine biodiversity is an essential food and economic resource. We need to find alternative solutions, combining conservation and exploitation, to protect biodiversity and the associated ecological processes, but also the livelihoods of the human societies that depend on them. To face this challenge, we need to establish new methods for the co-management of resources, proposing sustainable exploitation to keep productive habitats healthy, and seek new win-win options between conservation and exploitation, through larval dispersal for instance.

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5. The ocean and human health

Patrick Rampal and Denis Allemand

The interactions between the oceans and human health are numerous and complex, yet largely unknown. The ocean is the major source of food proteins for over a billion people, and plays an essential role in climate regulation, through its capacity to store and transport heat around the globe (cf. II.10), and to reduce the greenhouse effect by absorbing a quarter of anthropic CO_2 (cf. II.14). The ocean also produces a large proportion of the oxygen in our atmosphere. It contributes to many recreational activities (cf. V.17), boosting relaxation and psychological well-being. However, environmental changes affect the oceans by causing rising sea levels (cf. II.15), and the warming and acidification of the oceans (cf. II.9). In turn, these phenomena affect human health either directly (new opportunistic diseases) or indirectly (modification of the species distribution and therefore of fishing zones, salinization of soils, disappearance of arable land).

Distortions in marine microbial ecology

In the marine environment, climate change brings with it several opportunistic pathogens, which have recently led to massive deaths of marine organisms, including marine plants, urchins, molluscs, crabs and cnidaria. For example, on the coasts of Normandy, the infection of an edible shellfish, the abalone, by the *Vibrio harveyi* bacteria has been connected to an increased oceanic temperature caused by global warming. Normally present in the marine environment, these bacteria only cause high abalone mortality when the sea temperature is above 17°C. *Vibrio* bacteria can also affect crustaceans, fish and marine mammals.

These opportunistic pathogens may come from terrestrial or marine sources: several fungal or bacterial infections affecting different land animal species, including humans, can also contaminate marine organisms. For example, *Aspergillus sydowii* causes aspergillosis in gorgonians. In the late 1990s in the Florida Keys, this led to extremely high mortality among *Gorgonia flabellum*.

Other agents such as *Labyrinthulomycetes* (a kind of fungus) have shown their pathogenicity for eelgrass (a marine plant). They can be found in reef-building corals, where they contribute to the normal formation of holobionts: super-organisms made up of the host coral and all its associated organisms (bacteria, fungi, viruses, protists...). The shift from symbiotic function to opportunistic pathogeny can be facilitated by temperature changes in the marine environment. Very recently, it was shown that *Spirochaetes* (a bacteria group including the agents that cause Lyme disease and syphilis) were naturally present in Mediterranean red coral.

Fig. 1 – **Mucilage aggregates formed during toxic algal blooms of *Ostreopsis ovata* on the coasts of the north Mediterranean.** © L. MANGIALAJO / Ramoge. ■

Impacts on human health

Rising sea temperatures and anthropogenic modifications can alter the ocean's microbial and parasitic ecology in ways that affect human health. Thus, the brutal proliferation of these microbes, normally found exclusively in tropical waters but which are now being found in temperate waters, causes waters and shellfish to become contaminated by bacteria (*Vibrio*, *Listeria*, *Salmonella*, *Aeromonas*, *Clostridium*...), viruses (Norwalk-like, Herpes...) and parasites (nematodes, cestodes...). This creates a real health risk where populations are fragile as a result of malnutrition or immunosuppression. In the United States alone, around 15 million food toxi-infections per year are caused by eating contaminated seafood. Moreover, these pathogens spread much faster in the oceans than on land, because these environments are all easily connected, and it is impossible to isolate contaminated zones.

The proliferation of toxic algae is another problem connected to warming waters (cf. VI.11). These algae produce toxins which can affect many marine organisms, and which become more concentrated moving up the food chain, to cause human illnesses of variable severity, which are sometimes even lethal (ciguatera). They can also cause less serious respiratory, skin or neurological issues. The toxic effects of *Ostreopsis ovata*, a microscopic, single-cell algae which normally lives in the warm waters of tropical seas, are now being felt in the Mediterranean, where it causes respiratory diseases through the inhalation of aerosols, without direct contact with seawater.

Fig. 2 – **Dead beached whale after toxic algal blooms.** © J. CORY / Flickr. ■

Epidemiological monitoring

Given this situation, it seems necessary to better understand these transformations, through studies and epidemiological monitoring of surface and deep-sea ecosystems. Nevertheless, we must remember that although the ocean can be a source of infection risk or toxicological risk, it can also provide potential solutions that might, for example, help us understand the defence mechanisms by which marine organisms (fish, corals, molluscs) can resist these human pathogens, and to obtain bioactive compounds from them. It also provides a research model: remember that our understanding of the mysteries of fertilization, nerve physiology, memory or even immune processes owe much to the study of sea urchins, squid, molluscs or ascidians. Certain ecosystems, such as those of seagrasses, can reduce the number of pathogenic bacteria, and therefore potential infections among humans or marine organisms. Finally, exploration of sponges and cnidaria to discover future medications is only just beginning. These sources have already generated some successes, such as Trabectedin (ET743), the first cancer drug of marine origin to appear on the market (cf. VIII.7).

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6. Fishing and aquaculture: what are the challenges for food supply?

Didier Gascuel

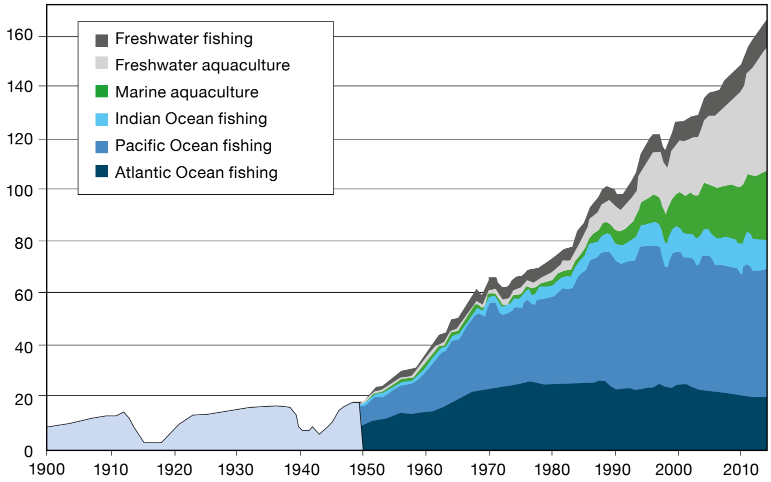
The sea feeds the human race. Fishing has long played a dominant role in this, being responsible for the bulk of production. Today, aquaculture is emerging strongly. Both sectors are facing environmental challenges which restrict their development, while demand for seafood products is growing strongly.

Tackling overfishing

Sea fishing expanded significantly during the 20th century (cf. IV.6). World production rose from around 5 million tonnes in the 1880s, when the first motorized boats appeared, to 20 million tonnes in 1950, reaching a peak of 86 million tonnes in 1996 (FAO, 2016). This growth was based on the increase in the size and power of fishing vessels and fishing gear, as well as the exploitation of an ever-increasing proportion of marine biodiversity, and began to slow in the mid-1970s. At that time, catches in the North Atlantic levelled off, as the production potential of this ocean had broadly been reached. The same pattern occurred in the 1990s in the Atlantic and then the Indian Ocean. For the last 20 years, world catches have been falling and peak production would therefore seem to be behind us once and for all.

Resources are limited and fishing is facing a global situation of overexploitation. The latest figures from the FOA show that 31% of world stocks are currently overexploited and 58% fully exploited. In Europe, the situation has been and remains particularly worrying. At the end of the 1990s, more than 90% of stocks were overfished, while the average abundance of resources living on the seabed was at just one-fifth or one-tenth of the levels seen at the start of the century. At that time, catches had halved compared with peak production observed in the 1970s. The situation has changed over the last 20 years, however, and vigorous management measures are being gradually introduced, at least in the Atlantic. Fishing quotas are becoming restrictive at last and subsidies enable excess fishing fleets to be reduced. This policy appears to be paying off: the proportion of overexploited stocks has sharply decreased (by about 60%) and the biomass of the main stocks being exploited appears to have increased by around 40% (AFH, 2016).

Forecasts offer little hope of very substantial increases in catches, either in Europe or globally. However, experience has shown that if the political will is there, fishing can be managed very



Change between 1900 and 2014 in world fish and aquaculture production, in millions of tonnes. Figures for 1900-1949: empirical reconstruction based on the scientific literature. Figures for 1950-2014: from FAO, 2016. ■

effectively. To guarantee economic profitability for fishing businesses, a situation where resources are scarce and exploitation is overly intense needs to give way to one of abundant resources and resilient marine ecosystems, with moderate exploitation. In the medium term, the goal is that the sustainable exploitation of the sea's resources should continue to provide us with 80 or 90 million tonnes, with an ecological impact that can be very significantly reduced.

Does aquaculture offer a solution?

Aquaculture has entered the fray to meet consumer demand. From its longstanding position as a marginal activity, it took off at the start of the 1980s and worldwide production increased from 2 to 27 million tonnes between 1980 and 2014. For freshwater products, growth was even stronger, rising from 2 to 47 million tonnes over the same period. Output comes largely from Asia and involves herbivorous species (carp, tilapia...). At sea, molluscs are very much predominant (accounting for 60% of production), followed by crustaceans. Sea fish and diadromous species (salmon) account for only a few million tonnes.

Aquaculture is also facing major ecological challenges, but of a different kind (cf. V.10), with the main issue concerning food supply. Seventy percent of world aquaculture production (including salmon farming) comes from species fed with artificial food such as oil and fishmeal, which absorbs a proportion of sea fishing output and thus exacerbates the problems of overfishing. One of the challenges facing aquaculture research is therefore to reduce the dependence of fish farming to fishing-based feeding. More broadly, the growth of the sector requires work on its inputs and impacts, and on the development of new, more sustainable productions.

Rethinking how we consume

Worldwide, sea fishing (excluding fishmeal) provides a little over 8 kg per person per year. This figure has fallen sharply (–2 kg since its peak in 1975), but the development of aquaculture more than compensates for this. Across all sectors, the average availability of aquatic food products is still growing strongly and reached 20 kg per person per year in 2014, accounting for 17% of animal protein intake. There are significant disparities underlying these figures, though. In France, our consumption has remained constant for 10 years or so at around 35 kg/person/year, including 24 kg from fishing, three times the global average ration to which we should logically be entitled. We are therefore eating too much fish, as we are undoubtedly eating too much meat. In other regions of the world, though, and specifically in the South, the availability of aquatic food products is declining. A recent study by the World Bank predicts that fish consumption in Sub-Saharan Africa will fall from 9.1 kg per person per year at present to 5.6 kg by 2030.

Fish still accounts for the majority of animal protein intake in many African countries, as well as in Asia's coastal countries and in most of the island states in the Pacific. These protein intakes are often deficient, and statistics from the United Nations show that three-quarters of the countries where fish accounts for more than 30% of animal protein intake are categorized as 'low-income food-deficit countries'. Yet malnutrition experts all agree on the importance of aquaculture products in addressing the food challenges of the next few decades. Fish does not just provide protein, but is also a source of elements that are essential for human health. In particular, it is rich in fatty acids and micronutrients that are today implicated in numerous nutritional deficiencies.

In order for fishing and aquaculture to continue meeting – in quantitative and qualitative terms – the growing demand from a world population that is itself increasing, they will therefore need to address environmental issues as well as those of social equity in the distribution of the food resources provided by the oceans.

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7. What challenges for genetic resources?

Sophie Arnaud-Haond

3.6 billion years ago, life appeared in the oceans, and it has been constantly diversifying ever since. The ocean contains 34 of the 36 large living phylums described to date, compared to 17 on land. Taking into account its three dimensions, the marine biome represents 99% of habitable space on Earth. Here, species are adapted to an extraordinary range of ecosystems and conditions, including exceptionally high pressure in the abyssal zone (< 4000 m) and the hadal zone (< 6000 m), exposure to extreme environmental conditions in terms of temperatures or chemical compounds (hydrothermal vents and cold seeps)... Because of this long history and the vastness of their environment, marine organisms offer a unique genome repertoire, which is extraordinarily rich and diverse.

Applications

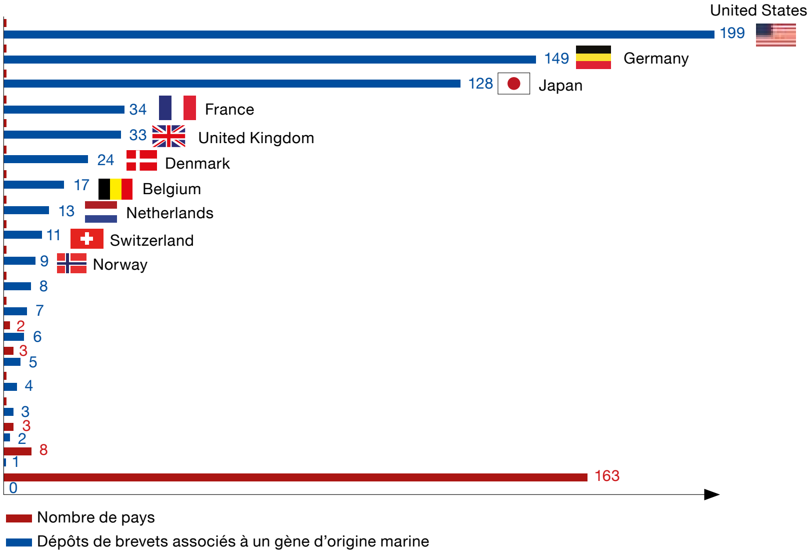
Molecules or genes of marine origin therefore have a very wide range of uses. An analysis of patent applications shows that the majority are filed in the medical and pharmaceutical domains. In research regarding cancer and HIV treatments, there are numerous studies and applications of molecules isolated from marine invertebrates. There is a similar interest in bioluminescent molecules in medical imaging. The cosmetics industry also uses various marine molecules, especially for their antioxidant properties, and the agro-food industry is showing increased interest in using molecules of marine origin, such as omega-3 and unsaturated fatty acids. Finally, biofuel can be produced using molecules from bacteria isolated from hydrothermal vents, and bio-remediation projects envisage the use of bacteria from chemosynthetic ecosystems to clean zones polluted by hydrocarbons (oil spills, offshore exploitation zones, etc).

Stakes, conservation and governance

In some cases, marine genetic resources (MGRs) already generate significant economic returns. For example, in 2009, the market for the above-mentioned use of hydrothermal bacterial amylase to produce biofuels was estimated at 150 million dollars per year. The exponential growth in the number of patent applications relating to marine molecules over the last 20 years suggests an acceleration in their exploitation, because new molecular biology techniques facilitate access to the genomes in question.

Simultaneously, global change (cf. VI.3) and the impact of human activity are exacerbating the degradation of the marine environment and its biodiversity. Certain fishing practices threaten the survival of the exploited stocks or bycatch species, or destroy habitats, whilst industrial waste, fertilisers and pesticides inevitably end up at the bottom of the ocean.

Yet the marine environment is only partly regulated to ensure equity in access to MGRs and the sharing of their benefits, and to protect the biodiversity on which they depend. These constraints are dealt with in a very fragmentary manner, in which the marine space is divided according to geopolitically rather than biologically coherent reasoning (cf. VIII.5). Although species present in Exclusive Economic Zones (EEZs) are managed by the United Nations Convention on the Law of the Sea (UNCLOS) and the Convention on Biological Diversity (with the Nagoya Protocol, which regulates access to genetic resources and sharing of the benefits they generate), there is no global framework for protecting the high seas. They are simply subject to the 'first-come, first-served' rule, with freedom considered to be the governing principle. However, although most of the diversity described to date has been in the EEZs, an unknown portion, often adapted to extreme conditions, is yet to be described in the high seas and deep oceans.



Difference between countries in terms of the number of patent applications associated with genes of marine origin. 2010 estimate. ■

Major challenges for future governance

These observations are clear, yet the United Nations member states are still struggling to reach a consensus to establish an international agreement, or even an associated authority, embracing both the ecological concerns for protecting marine biodiversity, and the economic and political concerns of rational and equitable exploitation of MGRs. It is this last subject which has long been the sticking point, because certain states (which have the resources to exploit MGRs) want to maintain the status quo regarding access to these genetic resources. Thanks to an agreement between developing countries and the European Union, it has been possible to simultaneously address the question of the governance framework required to protect the environment and the question of equitable sharing of the benefits of MGRs, in the same negotiation process. Another major accomplishment is the establishment of a preparatory committee for negotiations, with a view to formulating recommendations for the 2018 United Nations General Assembly. This committee will reach a consensual decision on the holding of a diplomatic conference to establish a unanimously acceptable governance framework.

Despite major advances, the path towards a solution that is consensual in both ecological and human terms remains long and winding. One of the great challenges of tomorrow concerns our capacity to reconcile biology and geopolitics, taking into account that marine organisms are often dispersive at some point in their life cycle, defying legal boundaries such as EEZs. So what solution would allow us to regulate access and sharing of the benefits, with a single system meeting both the criteria of Nagoya and those of the future governance framework for zones outside of EEZs? How can we ensure equitable access without imposing systems and controls which are costly in resource terms and potentially damaging for academic research on biodiversity, an essential pillar of conservation strategies? What does the future hold for the notion of the common heritage of humankind, which some countries defend and others dismiss? And finally, how can we effectively protect a space so vast that it covers 70% of our planet's surface, and the resources in it?

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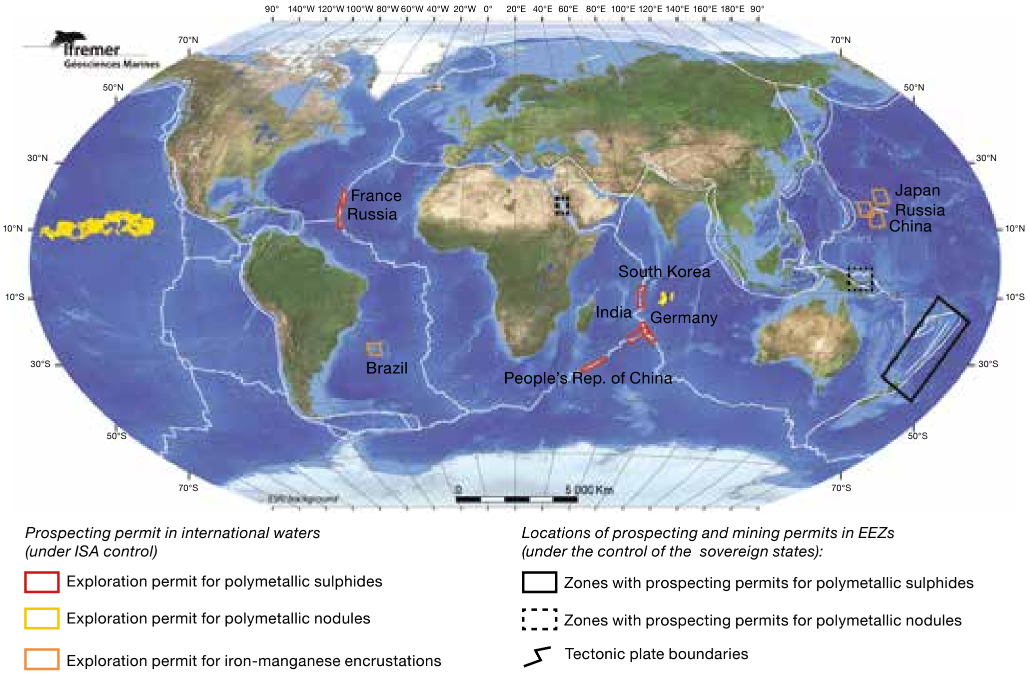
8. What challenges for mineral resources?

Yves Fouquet

For several decades, humans have taken an interest in the deep seas, from several angles: scientific, economic, technological and educational. However, industry and the states are more specifically interested in oceanic metals, with a view to their potential exploitation. Generally, this concerns three types of mineralization: nodules, manganese crusts and hydrothermal sulphides (cf. V.5). Nodules and crusts are primarily made up of iron and manganese oxides. However, the economic interest of the three types of mineralization depends on their concentrations of base, precious or rare metals. New challenges are emerging, at the crossroads of fundamental research, economic interests, and environmental protection.

Scientific challenges

Scientific discoveries have advanced our understanding of certain forms of mineralization, but there is still much to learn, particularly to understand the processes for the transport, concentration, and dispersion of metals. The most crucial question for industrials is that of how and where mineralization forms in the highest volumes and with the greatest concentrations of base, precious or rare metals (since the largest mineralization is not necessarily the richest). This knowledge is vital, to effectively locate mineralization, determine the biodiversity and dynamics of ecosystems, prepare impact studies and define the conditions for sustainable exploitation.



Locations of permits for deep-sea mineralizations. ■

Technological challenges

Effective exploration to locate and evaluate resources on different scales is dependent on technological advances. For example, conventional exploration techniques can effectively discover active hydrothermal sites, but the industry is interested in inactive deposits. There are almost 200 known hydrothermal fields, but only a few dozen of the known sites are inactive, even though there are undoubtedly far more inactive sites than active sites. The technological challenge is, therefore, to develop combinations of sensors to conduct effective exploration strategies on different scales, in order to rapidly locate fossil sites. For nodules and encrustations, the resource estimates are based on bathymetric maps. The resolution of these (50 to 100 m) is not high enough to recognize and evaluate mineralized zones and devise mining and habitat conservation strategies. We therefore need to produce high-resolution maps, near to the seabed, using AUV-type autonomous vehicles.

Since this is a new industry, it will be necessary to master technologies for extracting mineral ores, bringing them to the surface and processing them on land, with minimal environmental impact. Currently, the 'deepest' mines (< 200 m) are for Namibian and South African diamonds. Nodules are located at depths of over 4500 m, encrustations between 400 and 4000 m, and sulphides on average at 3000 m. We therefore need a technological leap to move on from diamond mining to deep sea mineral ore mining. Finally, the improvement of ore processing technologies is a major technological challenge. For nodules, processing the ore can account for up to 60% of the exploitation cost. Moreover, the demand for rare metals increases the importance of processing ores to extract trace metals, as by-products of base or precious metal mining.

Legal challenges

In international waters, the International Seabed Authority (ISA) has established specific legislation for nodules (in 2000), sulphides (in 2011) and encrustations (in 2012). The ISA has currently allocated 26 prospecting permits, with 18 of these allocated since 2010 (Fig.). Discussions are underway to define the legal conditions for allocating mining permits. In exclusive economic zones (< 200 nautical miles), it is state legislation that applies (cf. VII.9). In France, as in other countries, the mining code is being reviewed, in particular with a view to taking societal and environmental factors into account.

Environmental challenges

The environmental impact can differ widely according to the type of ore. Nodules and encrustations are low-grade ores that cover large surfaces (several kilometres or tens of kilometres long). In contrast, hydrothermal mineralizations are high-grade but very localized ores (with an average diameter of 200 m). The environmental challenges are therefore very different. Exploration can also represent an opportunity to improve our knowledge of biodiversity. At sea, as on land, very few of the mineral occurrences discovered are of economic interest (less than 1 in 100). Exploration will therefore provide information about vast domains that will not be mined, thus boosting our knowledge of biodiversity. The data required will allow us to define zones requiring protection and to impose impact studies where mining occurs.

Geopolitical challenges

Like energy, water and food, the stakes of accessing metals are high, because of heavy demand from the large emerging countries (China, India...) and because of global demographic change. For France, one issue relates to the knowledge of resources in the exclusive economic zone (11 million km^2). The industry is interested in mineral ores with a high added value compared to their equivalents on land. The aim is, therefore, to find high-grade ores, in order to guarantee profitability and minimize environmental impact. This makes sulphide mineralizations a prime target. The core issue for the developed countries is diversifying sources of supply, and deep-sea mineral ores could aid this diversification.

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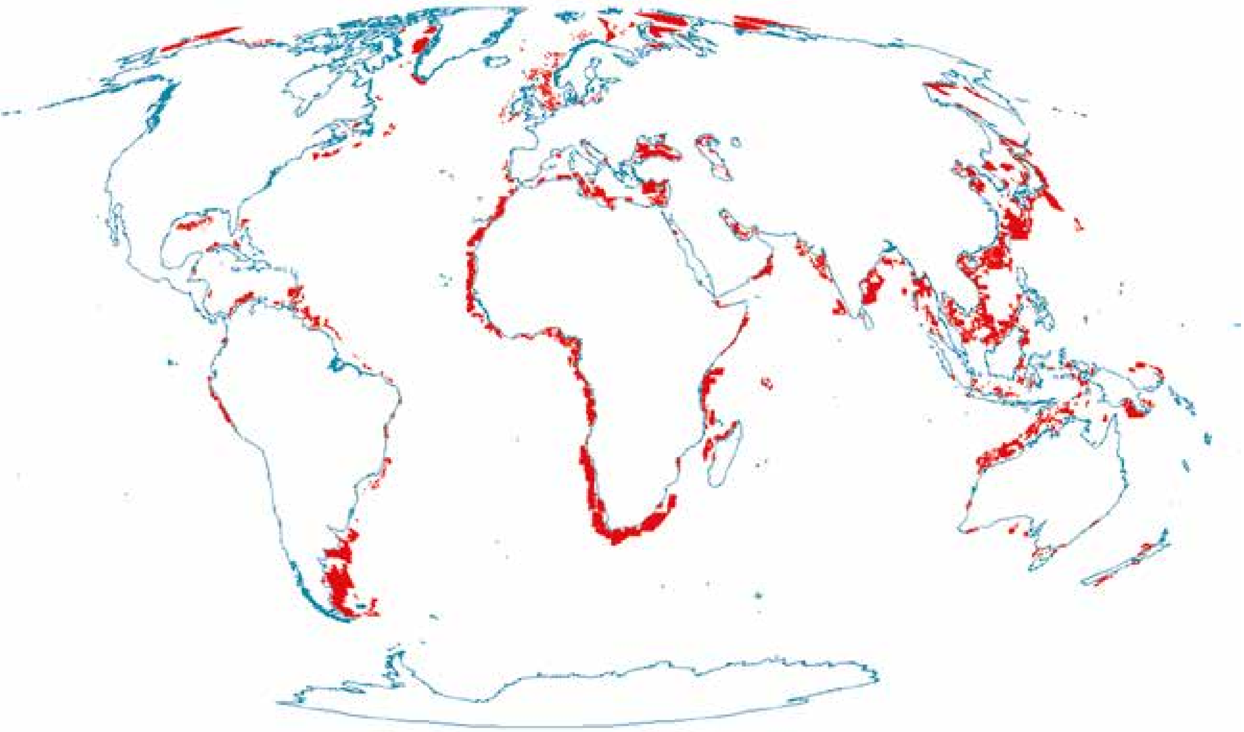
9. What challenges for energy resources?

Jean-François Minster

Population growth and the associated development needs mean that humanity today requires ever-increasing amounts of energy, especially as almost 2 billion people have no access to modern energy forms. Since energy is essential for all human activities, its cost must remain compatible with the value of what it allows to create. At the same time, the challenges of climate change mean that we need to modify energy production systems drastically and rapidly, at a global scale. In these conditions, marine energy resources, offshore hydrocarbons, and renewable energies, offer a potential that mankind cannot easily forgo. However, for the two types of resources, exploitation presents qualitatively different technological and industrial maturity levels, costs and challenges.

Offshore oil

Offshore production amounts to approximately 30% of current global oil production and 27% of gas production. Given the importance of hydrocarbons in global energy production (over 50% of primary energy), these marine resources are essential for humanity today, and will undoubtedly remain



Map of marine oil exploitation permits in 2013. Source: IHS Markit. ■

so for several decades. Moreover, they are thought to represent a quarter of the undiscovered 'conventional' resources.

Exploration permits are distributed across all continents (Fig.) and are allocated by states, in their Exclusive Economic Zones. Therefore, the exploitation of hydrocarbons is one of the key reasons for demands to extend the EEZs established as part of the Convention on the Law of the Sea. It is also one of the main reasons for existing or potential maritime conflicts, from the seas of the Far East, to the south Atlantic and even the Arctic. There are 17,000 offshore production platforms scattered across the oceans, with half of these placed at shallow depths. The proportion of deep sea production (at depths of up to 3000 m) has been constantly rising since the end of the 1990s, because technological advances have made it competitive.

The safety and environmental challenges are of course inescapable. This encourages major evolutions in design and technologies for exploitation, aiming to reduce emissions as much as possible. These developments draw on technological advances in all domains (materials, robotics, simulation of complex systems, measurements...). This challenge also requires increased and open monitoring of facilities and sites, as well as immediate intervention capacities. Sometimes, this leads to operators (such as Total) refusing to embark on certain exploitations, such as oil exploitation in the Arctic, which is considered too dangerous for the environment. Cutting greenhouse gas emissions is of course a crucial issue. Significantly reducing gas flaring of associated methane production is therefore an important objective, and the industry is working actively to achieve it.

However, the recent evolutions in global energy production, particularly hydrocarbons, affect offshore production: the surge in the production of bedrock hydrocarbons (shale gas and shale oil in the United States) and the ensuing 'commercial war' with the OPEC and the other producer countries, necessitate a drastic reduction in the cost of exploitation systems, to keep them competitive. This has led to major redefinitions of new projects, and to delays in (or even cancellations of) new offshore investments, causing severe problems for the industry's entire value chain. Finally, the rapid transformation of the whole energy production industry creates industrial strategy challenges for the entire sector, while the changes in the world and in economic activity can create difficult situations.

Marine renewable energies

The exploitation of marine renewable energy resources is another, still emerging sector. It is very much a minority sector in terms of global renewable electricity production, and still requires important technology developments. However, these solutions are potentially interesting, particularly for isolated places such as islands. To determine whether these energy resources are important, it is necessary to distinguish between marine resources (very plentiful); potentially exploitable resources (due to their proximity to the coasts and to consumption zones); and finally, economically exploitable resources (today or in several years). It is this last value that determines the possibilities for investment in these solutions.

Wind resources provide for a practically mature technology: offshore wind energy. Because offshore winds are more regular and often stronger than those on land, and offshore wind turbines cause less usage conflicts near to the coasts, offshore wind farms are constantly growing, particularly in northern Europe. However, we need to ensure that the deployment, maintenance, safety, competition with other users of the marine space and electrical connections do not generate excessive additional costs. Depending on the geographical locations and the public policies of countries, electricity from marine renewable energies can sometimes be produced at costs equivalent to those of other renewable energies (source: ADEME).

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10. What is the future for the Arctic routes?

Thierry Garcin

The current level of interest in the navigation of Arctic waters is largely the result of global warming. Over the last four decades, satellite observation has provided proof of the reduction in the surface area and thickness of the summer polar ice cap. In 2015, its maximum extent was 4.41 million km^2, a loss of 1.81 km^2 compared with the average for 1981-2010. In the specialists' view, the polar ice cap will eventually disappear completely during the warmer months of the year. Should this indeed happen, the more direct transpolar sea route would supplant the current maritime paths, which are complex, risky, lengthy and costly. Currently, the preferred passage for ships crossing from the Pacific into the Atlantic and vice versa is the Northern Sea Route *via* Russia. It is noteworthy that in September 2008, both this route and the Canadian Northwest Passage were, for the first time, free of ice for several days.

Two very different routes

While both maritime paths, *via* Russia and Canada, share the same extreme environment of darkness, cold, ice, they are not comparable.

To begin with, Canada's legendary Northwest Passage, which was first sailed end to end by Norwegian explorer Roald Amundsen between 1903 and 1906, is fraught with difficulties. While access to it is relatively straightforward (from Baffin Bay in the east and the Beaufort Sea in the west), ships have to follow a meandering route, the straits are often shallow (the Victoria Strait has a depth of 22 metres), drifting ice is an unpredictable hazard, the Arctic summer is highly conducive to fog formation, and stranding is not uncommon, with occurrences in 2009 and 2010. Lastly, the maps of the region are incomplete and inaccurate. However, in 1969, the Americans were able to sail a 150,000-tonne oil tanker, the Manhattan, through *via* this route; in 1985, an icebreaker, the Polar Sea; and even, in 2005, a navy submarine, the USS Charlotte, all much to the chagrin of the Canadians who – like the Russians – regard these straits as territorial seas rather than international waters where no prior agreement is needed for 'a right of innocent passage'.

Furthermore, the Northern Sea Route (Fig. 1) is much more easily navigable, following the line of the Russian Arctic islands (Wrangel, New Siberia, Severnaya Zemlya and Novaya Zemlya) and skirting the major river estuaries of the Lena, the Ienniseï and the Ob in the east and centre and the inhabited peninsulas of Taïmyr and Yamal in the west.

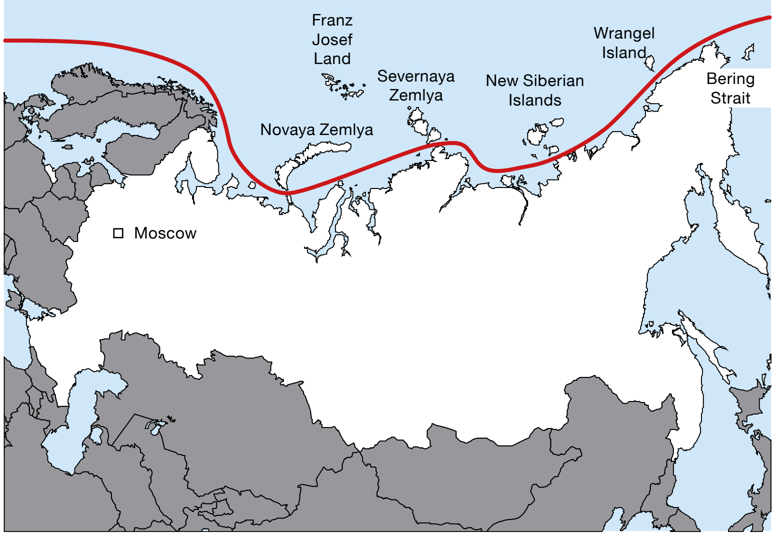

Fig. 1 – **Russia's Northern Sea Route.** © T. GARCIN / E. GODET. ■

The coastal sea is shallow, however, especially in the east, and the Laptev and East Siberian Seas are notorious for ledges – an icebreaker was even lost to the ice in 1983. Nonetheless, while search and rescue operations are always challenging, their implementation is quicker and less hazardous here than in the Canadian Arctic.

Main hazards

The coasts of far northern Canada are exceptionally remote, rugged and sparsely populated (despite the presence of highly dispersed, poorly equipped Canadian Rangers drawn from the indigenous population). In particular, they are vast: 40% of Canada's national land mass is in the Arctic. Sailing this route requires a vessel with a reinforced hull, special navigational equipment, a trained crew (necessarily costly) and a non-perishable cargo. In the event of a collision or accident, a ship can be at a standstill for a whole winter and assistance is very slow to arrive in the region, even by aeroplane. In January 2017, a Polar Code developed by the International Maritime Organization (IMO) came into effect, describing the numerous conditions to be met. An oil spill would very quickly become an environmental disaster here, since oil is not easily dispersed in icy water. In the US state of Alaska, the Exxon Valdez oil tanker disaster in 1989 polluted 1,700 km of coastline and the cost of clean-up to Exxon was very high.

The polar routes are certainly shorter. To cover the 21,600 km from Rotterdam in the Netherlands to the Chinese port of Dalian takes 48 days for a cargo ship sailing *via* Gibraltar, Suez, Bab-el-Mandeb and Malacca, compared with just 35 days *via* the 14,600 km Northern Sea Route.

Fig. 2 – **The Russian nuclear-powered icebreaker, the Yamal.** © Pinkfloyd 88a ■

Chinese ships sailed the Russian route both ways in 2013 and 2016. The associated price tag was high, though, particularly because of the frequent need for a Russian nuclear-powered icebreaker to act as an escort, as the only type of vessel in the world capable of breaking through ice between 2 and 3 metres thick (Fig. 2). Russia also uses the icebreakers to promote the eastern Siberia region, engaging in a kind of polar cabotage and putting the river estuaries and their hinterland on the map (despite the melting of the permafrost).

While the outlook for the Northern Sea Route is more certain for the next 20 years, to the benefit of the Chinese ports (two-thirds of the world's top 20 ports are in China), traffic will remain very modest in global terms: the volume for 2016 was 6.9 million tonnes, an increase of 33% from 2015. Certainly, 2016 saw five Chinese ships unloading in the Yamal peninsula, but foreign vessels account for just 20% of the total. Only 19 ships sailed the Northern Sea Route from end to end, mostly from east to west, with 72% of their cargos being coal.

Ship owners and insurers argue that the three major transoceanic routes (the Panama and Suez Canals and the Straits of Malacca between Malaysia and Indonesia) will remain the sovereign routes for commercial navigation for decades to come. Moreover, the Panama Canal has recently been modernised and enlarged (and can now accept vessels transporting up to 14,000 containers), while the capacity of a 72 km stretch of the Suez Canal was doubled in 2015.

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11. Coastlines and public policy: integrating the challenges

Nacima Baron

Managing the coastline in a context of uncertainty

Coastal areas are facing many challenges. The strip of land at the sea only occupies 4% of France's surface area but is home to 6 million people, *i.e.* 10% of the total population, with density and artificial land cover rates three times higher than average for mainland France. Its ecological degradation continually worsens, influenced by three factors: the discharge of pollutants from continental river basins, the increased exploitation of resources found on the coastal fringe and in coastal waters, and the ecological footprint left by the concentration of people and human activities. Damage to natural habitats and living species, chronic or accidental pollution, and submersion and landslide risks caused by coastal erosion can be seen to varying degrees along the entire coastline. A lot of the forecasting work carried out at national, European and global levels at varying horizons (2050, 2070 and 2100) paints a gloomy picture for large parts of the French mainland and overseas coasts. Ongoing research point to a dynamic, unstable coastal system that is uncontrolled and vulnerable. Coastal mobility trajectories appears for every scale of time and space, where the most populated, the lowest-lying and most friable areas will be much less able to adapt to the effects of climate change. It is clearly down to coastal vulnerable communities facing uncertainty to develop the resilience required for the long term, by establishing agreements based on shared choices in conjunction with public policy tool.

Fig. 1 – **Built 200 m from the shore in the 1960s, the 'Le Signal' residential block at Soulac-sur-Mer was threatened by erosion and evacuated in January 2014.** Source: France 3 Aquitaine. ■

France already has a highly structured regulatory framework of integrated approaches encompassing the stakes and stakeholders (*e.g.* integrated coastal management, integrated sea and coastal management). This framework is built around European (water and marine habitat directives) and national legislation. One of its pilars is the law on coastal protection and development, enacted over 40 years ago to regulate coastal development, protect it from the excesses of speculation and to enable public access to the shores. It was recently updated to take on-board current concerns and to give public initiative a more regional but no less conflictual approach. However, this framework is challenged by two major factors of change.

The first is the fact that many public policies remain based on divisive paradigms such as 'fragility versus coastal attractiveness' or one-dimensional approaches to anthropogenic pressure and cumulative impacts, now evolving to take a more systemic stance. The second shift is the emergence of an array of initiatives from organizations involved in the French coast, resulting in a plethora of charters, calls and recommendations on good governance and planning, causing a great deal of confusion. These organizations include scientific and industrial lobbies and, following decentralization and territorial reform, a group of entities and associations that may or may not have links with the authorities. This creates fertile terrain for expression and action, a variety of messages and a host of incentive schemes concerning the coast but also, for researchers, a multitude of areas for field observation. Yet does this public mobilization, which is much wider than it was a couple of decades ago, really have a political effect? Are coastal areas better managed in terms of risk today? Experimental problem-solving procedures (in Brittany, Languedoc and Normandy as part of the Liteau programme, for example) show that there are high social expectations for operational capability and a huge effort for intelligibility. They all conclude that public action definitely needs to be 'decompartmentalized'.

Organizing public action on the coast

Given the increasing risks of submersion, the most urgent requirement is to build up social and spatial solidarities uniting the coast and inland areas and fostering dialogue between residents and the local authorities. The next priority is to better formulate environmental goals and the sustainability issues affecting the ocean's productive systems. In this respect, decompartmentalization means more dovetailing of protectionist policies with policies that support the traditional sectors, such as fishing or shellfish farming, naturally concerned with resource quality or biomass quantity. Thirdly, this also implies shared decision-making *via* consultation and participation, bringing on-board residents and users of the coastal areas. A coastal approach that covers the 'common' resource and a 'no regrets' strategy obviously requires collective processes, interpretations and negotiations. Finally, integration of policies is also about mindset as it challenges the conventional divisions between natural and cultural heritage and approaches that are often split between the coast's material and immaterial resources. Solving conflicts over coastal occupation and development, which is a fundamentally political issue, need bringing cultural change among stakeholders and accepting the time frames and conditions for project formulation, public deliberation and the friction that this pooling of resources will inevitably generate.

Fig. 2 – **Railway along the island of Sainte-Lucie and the Bages-Sigean lagoon.** The Sainte Lucie Port-la-Nouvelle regional natural reserve, Aude. © C. FERRER. ■

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12. The blue economy: perspectives and challenges for the seventh continent

Olivier Thébaud

On a planet which is now considered too small, many see the ocean as a new frontier of the global economy. As a provider of energy, goods and services, and a vector for trade, the ocean is already an essential component of global economic development. All over the world, investments in 'blue growth' appear to be on the rise, supported by economic sectors rooted in the history of human societies. New sectors filled with potential and promise are also setting their sights on the ocean.

A need for improved assessment

There is currently no shared international definition of the maritime economy, and no unified statistical system to track its evolution. Nevertheless, a consensus is emerging that the 'blue economy' should be defined as all the economic activities connected to the sea and coast. These activities are based on the extraction of resources (living, energy or mineral), the exploitation of the physical properties of the sea and seabed, the exploitation of remarkable maritime and coastal sites, and the transformation and processing of biological resources. It also includes manufacturing and service sectors upstream of industries which directly exploit the sea and the coast. The blue economy encompasses established sectors, such as maritime transport, shipbuilding and ship equipment, as well as traditional aquaculture and the processing of marine produce, maritime and coastal tourism, conventional offshore oil and gas exploration and exploitation, aggregate extraction and port infrastructures. In addition to this, there are highly technological sectors (such as offshore parapetrolic activities, undersea cables or the construction of specialized ships) and emerging sectors, such as the exploitation of marine renewable energies (cf. V.7, Fig. 1), the exploitation of energy resources and deep ocean minerals (cf. V.5), new forms of aquaculture (cf. V.10), marine biotechnologies (cf. V.12), and observation and surveillance activities.

In principle, analysis should take into account the natural capital represented by marine ecosystems, and all of the services that these ecosystems provide. Nevertheless, attempts to evaluate these services at international level remain highly disparate and extremely variable, making any global-level aggregation

Fig. 1 – **Offshore wind farm off the coast of England, in the North Sea.** © Ifremer / O. DUGORNAY. ■

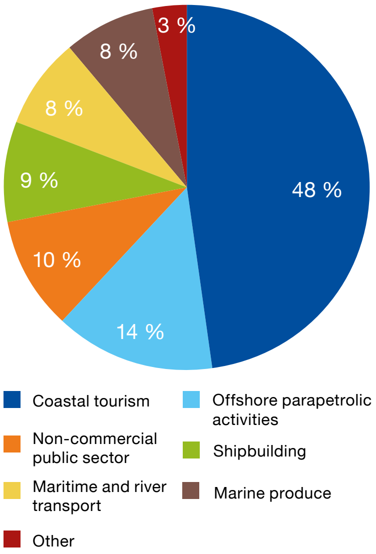

Fig. 2 – **Value added in 2011, in €M.** Source: Données Économiques Maritimes Françaises, Ifremer ■

difficult. Therefore, these efforts to characterize the real economy are so far limited to evaluating the contribution to economic production and to employment in maritime sectors. In France, the maritime economic data produced by Ifremer (Fig. 2) also measure the importance of non-commercial public services (defence, supporting maritime activities and professionals, environmental protection, research).

An economic sector with global impacts

According to a recent study by the OECD (2010), the maritime economy defined as such contributes at least 2.5% of world gross value added (GVA), equating to 1500 billion dollars. A third of this value added comes from offshore oil and gas extraction, a quarter comes from coastal tourism, and almost a quarter comes from port transit and manufacturing of maritime equipment. According to the study, maritime activities as a whole support 31 million direct full-time jobs, or 1.5% of jobs on a global scale. Although the maritime fisheries sector makes only a small contribution (1%) to global GVA, it supports 36% of the jobs created and plays a major role in food security (cf. VI.15). The coastal tourism sector represents almost a quarter of the jobs created. According to the OECD, the blue economy should grow significantly over the next two decades, driven by growth in the world population and its concentration in urban and coastal zones, and by increased wealth at international level, particularly in emerging economies.

Challenges to overcome

This growing demand for ocean resources and spaces intensifies and diversifies interactions between human maritime activities, both direct and indirect (*via* ecosystems), from the local scale to the global ocean. The future of the blue economy largely depends on good management of these interactions. One major challenge is to set limits on exploitation, in order to ensure that marine ecosystems remain able to provide indispensable goods and services for human development. The second major challenge is to allocate access to the spaces, resources and services provided by ecosystems, within these limits. Yet despite the many public policies in place, we face ever-increasing problems from pollution (cf. VI.12), overexploitation of living resources, climate change (cf. VI.3), and the acidification (cf. II.9) and deoxygenation of the oceans (cf. II.8).

Faced with the wide range of sectors to be considered and the complexity of interactions between activities, the solutions necessarily involve the integration of sectoral policies, and the establishment of methods for coordinating the different regulators of marine activities (cf. V.3). Today, one of the main frameworks for this is ecosystem-based management and the planning of maritime space. Recent works in this domain emphasize the importance of clearly identifying management objectives, making the best possible use of available information (even if incomplete) and involving stakeholders in the creation of new institutional frameworks. In the face of uncertainty and changing economic and environmental contexts, we need to learn as we go, following the principles of adaptive management. Above all, the future of the blue economy is therefore a question of collective choices, based on shared global knowledge.

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13. The ocean: a common good?

Agnès Michelot

For historical reasons, but also due to the technological, economic, political and strategic stakes, the ocean is the oldest and most complex common good. The seas make up 97% of habitable space on the planet and play an essential role in regulating the climate. The large amounts of maritime traffic are fundamental for the economies of many countries. At the same time, the ocean is the recipient of all our waste (including nuclear), pollution, and chemical substances from natural and synthetic products. Overfishing and degradation of the trawlable seabed make the exploitation of marine resources equally worrying. Moreover, the oceans are acidifying at a dizzying pace (cf. II.9), and human activities threaten the marine environment on a huge scale: we may soon reach a point of no return. The coastal environment is particularly threatened, because of continuous contamination by telluric pollutants (coming from the earth *via* watercourses) and atmospheric pollutants (which fall into the sea from suspended pollution in the air).


The Fisherman of Kajikazawa, Katsushika Hokusai, 1830. British Museum. ■

The protection framework

Faced with the global ecological situation of the ocean and the limitations of the existing protection mechanisms, which are too sectoral, as well as the ever-growing economic pressures on resources, the international community is examining possible adaptations of the legal regime applicable to marine species outside of national jurisdiction. The 1982 Montego Bay Convention on the Law of the Sea established a general framework, stipulating that ‘States have the obligation to protect and preserve the marine environment’ (Article 192). The Convention identifies different marine spaces, from territorial seas to the deep ocean floor, and sets out the applicable legal regime (cf. VII.9). It also lays down rules for the exploitation of natural resources. Beyond the territorial sea, it defines the regimes for the seabeds and overlying waters. The regulations apply to marine biological resources (fish stocks), non-biological resources (sand, gravel, gas, oil, nodules and even ocean ice), and other resources produced from elements of the ocean (energy from water, currents and winds). Above all, the law of the sea makes an important distinction between marine spaces under national jurisdiction, and therefore under state control (the territorial sea, continental shelf and exclusive economic zone) and international spaces (the high seas and deep ocean floor, or the ‘Area’). The historically original principle of freedom regarding the high seas and their common usage by all states, in respect of international law, covers shipping, fishing, laying of cables and scientific research. The deep ocean floor consists of the seabed and subsoil beneath the water mass of the high seas, and is recognised as the common heritage of mankind. Consequently, no state can claim or exercise sovereignty over these spaces, or attempt to appropriate them. Mankind is represented by the International Seabed Authority, which ensures that activities are conducted in the interests of humanity as a whole, with an equitable sharing of financial and economic advantages.

The limitations of the framework

There is therefore quite a comprehensive general law of the sea. It delimits marine spaces, regulates the activities of resource access, exploration and exploitation, and provides for the protection of the marine environment. However, the current law is guided by the idea that the global ocean is a common good. Although it establishes a material framework for protection and international cooperation, it is primarily driven by the desire to balance the interests of developed and developing states, and of coastal and landlocked or geographically disadvantaged states. The protection of the marine environment does not lie at the heart of Part XI of the 1982 Convention, which aims to promote the harmonious development of the global economy. The 1994 Agreement aims to support equitable management of natural resources to supply the market, and thus moves away from treating the ocean as the common heritage of mankind. Yet the concept of a common good has undergone a certain revival, to guard against the tragedies of globalization by questioning the supremacy of an absolute sovereign state, the law of the market and property rights. There is a move towards a very different world-view.

Moreover, the law of the sea faces several difficulties and new challenges, which show the importance of adapting ocean governance approaches. Recent discoveries of marine microorganisms in the high seas and very often in the seabed blur the line between the high seas and the 'Area'. We therefore need to find a legal regime which takes into account this evolution in biological oceanography, because the rules for the deep ocean floor do not cover the exploitation of these newly identified resources. Similarly, marine protected areas tend to overlap with the high seas, to limit the impact of high-seas fishing and control fishing for species on the boundary of the EEZ. This phenomenon can be seen in the Mediterranean, the North-East Atlantic and the Southern Ocean. Meanwhile, as rising sea levels threaten to make certain territories uninhabitable through flooding, we need to consider maintaining the ownership of these maritime spaces to ensure that they do not 'fall' into the legal regime of the high seas. Finally, the coastal zone, and with it the coastal states, play a considerable role in protecting the marine environment, given the enormous impact of telluric pollution. However, the protection of the marine environment is beneficial for humanity as a whole, so the role of the state needs to be reinterpreted, making it a guardian of the common interest.

These new challenges demonstrate the urgent need to establish a governance system for the global ocean that takes us beyond the ideas of near-exclusive ownership (such as it applies to spaces under national jurisdiction), of sharing benefits (in the Area) and of freedom of exploitation (in the high seas). We need to arrive at a shared management of marine resources, so that we can benefit collectively from their uses. The ocean treated as a common good would be managed and protected as a unique and cohesive space, for which states would share collective responsibility. The current international negotiations will allow us to determine whether the international community will back this approach of recognising the ocean as a common good. In any case, posing the question of the commons reopens a reflection on solidarity and justice in the long term. It is essential for this reflection to be applied to the oceans, because of their importance for ecological balances.

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14. The sustainable development goals for the ocean

Jean-Paul Moatti and Philippe Cury

A universal agenda for sustainable oceans

The 17 Sustainable Development Goals (SDGs) of the United Nations' 2030 Agenda are intended to eradicate poverty, protect the planet and ensure that all humans live in peace and prosperity over the next decade. As is the case for terrestrial environments (SDG 15), the ocean and marine environments have been assigned their own specific goal (SDG 14), which aims to '*conserve and sustainably use the oceans, seas and marine resources for sustainable development*'.

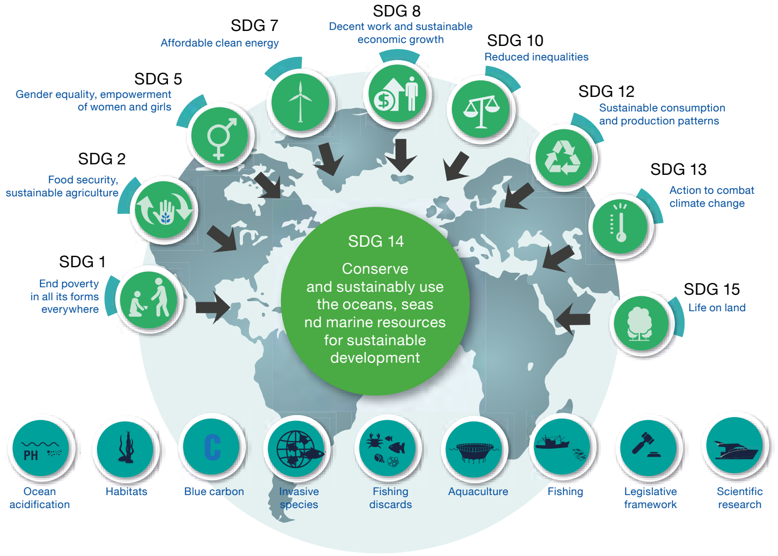
SDG 14 provides an opportunity to tackle some of the complex challenges of ocean sustainability through coordinated international cooperation across industries, involving a wide range of stakeholders. Seven targets have been devised for the sustainable use of the oceans, coastal areas and their biodiversity. Target 1 concerns the adoption of measures to reduce stress factors and restore the structure and functions of marine ecosystems, to ensure the marine environment is healthy and therefore productive. Target 2 seeks to adopt measures to promote 'blue growth', focusing attention on further efforts to support responsible fishing and aquaculture, using political, regulatory and economic means to encourage efficiency and the recovery of fishing discards. The aim of Target 3 is to adopt measures leading to political, legal and institutional reforms to support effective ocean governance. These measures will create a legal and institutional framework that protects inhabitants and biodiversity beyond national jurisdictions, reform the regional organisations responsible for managing the oceans, and improve the coordination, consistency and effectiveness of the United Nations' system for ocean issues. Target 4 sets out to effectively regulate harvesting and end overfishing by 2020. For target 5, the goal is to conserve at least 10% of marine and coastal areas by 2020; for target 6, it is to eliminate fishing subsidies that contribute to overcapacity and overfishing. Lastly, target 7 aims to extend the economic benefits of the sustainable use of marine resources to Small Island Developing States and the least developed countries.

Multiple goals for investigation

No matter how ambitious SDG 14 may be in regard to maintaining the health of the oceans, it is not possible to separate it from the other, interdependent goals of the 2030 Agenda. They will need to be achieved simultaneously: ensuring the good health of the oceans cannot be divorced from food security, eradicating poverty, reducing inequality or from patterns of consumption, or indeed from the preservation of biodiversity and the fight against climate change (Fig. 1). The challenges we face are global and our responses to them must consider international dynamics and in particular, the balances between North and South. New areas such as equitable fishing and access to renewable resources are thus emerging as these goals are achieved. Today, more than two-thirds of the marine resources consumed in Europe are produced primarily in the Southern countries. Of the 30 countries where fish is the main source of animal protein, 26 are developing countries where 47 million people earn their living directly from the seas. Illegal fishing, which accounts for around one-third of the world's fish catch (cf. V.8), makes employment less stable.

Advances in research are a *sine qua non* for achieving the sustainable development goals, given the complex nature of the dynamics and interactions. The ecosystem approach to fishing, which aims to reconcile conservation with biodiversity and exploitation, has shaped the approach to the marine environment for the last decade. Today, a more ambitious, inclusive framework is emerging with the 2030 Agenda. This new approach is redefining the aims and themes of scientific research by broadening their scope and factoring them into public policies (developing socio-ecosystem scenarios such as those of the IBPES).

Within this overall context and in the face of increasing demand, the scientific community must make every effort to explore the future of marine ecosystems, as well as the possible trajectories for socio-ecosystems leading to environmentally, economically and socially desirable outcomes. It also needs to develop a long-term scientific strategy which will improve its ability to provide inclusive multidisciplinary expertise that links global challenges with local requirements.



SDG 14 occupies a central position in the 2030 Agenda, with links between its objectives and many of the Agenda's other goals. Such interdependencies provide opportunities to develop synergies and require finely balanced compromise from stakeholders. This new conceptual framework considerably broadens the prospects for ocean research and governance. ■

A two-fold challenge: integrating knowledge and governance

'Sustainability' has often been something of a mantra, and this has not helped to reverse the long-standing patterns of global warming, biodiversity erosion, overexploitation of resources or increasing inequality. Today's ambitions are global in scope and new proposals for governance are emerging. Recommendations for a central register of ocean commitments as a transparent basis for monitoring national efforts, the development of coordinated policies for regional ocean measurements and partnerships and consideration of an integrated thematic appraisal of the implementation of SDG 14 offer new and innovative options in terms of governance. A thematic review of oceans and coasts worldwide would underscore the central role of the oceans in sustainable development and provide a platform for tackling the key links with the other SDGs relevant to the oceans.

SDG 14 represents a unique opportunity to help us redefine development, combining it with the supporting research that is necessary for this transformation. It is time to introduce a different way of framing and formulating questions to arrive at joined-up strategic environmental, economic and social recommendations. The interdependencies and compromises coming out of the 2030 Agenda must be painstakingly reviewed. This necessitates a shared effort to move the world's oceans towards not just ecological, environmental or social sustainability, but to all three at once.

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- Part Two -

What is the ocean?

Previous page:

Shoal of *Lutjanus kasmira* perch off Fakarava in the Tuamotu Archipelago, French Polynesia.
© T. VIGNAUD / CNRS photo library. ■

1. Introduction

Catherine Boyen, Pascale Delecluse, Françoise Gaill, Catherine Jeandel and Catherine Mével

We are all familiar with the ocean but, by its very nature, this massive volume of water, estimated at 1,370 million km^3 and covering 71% of the earth's surface, remains difficult to apprehend and is therefore far from having revealed all its secrets.

Its volume, the origin of the water that makes it up and the morphology of the seabed are very closely connected to our planet's history and the way it works. It is the presence of liquid water than led to early earthly life, no doubt in environments similar to the present-day hot springs. Marine species underwent various adaptive processes, and gradually left the water to colonize the land.

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Sea water is a chemical solution, the composition of which varies according to natural input and entrapment, but also human activity. Its colour reflects the nature and abundance of particulate matter, especially phytoplankton. Exchanges between the ocean and the atmosphere influence oxygen and carbon dioxide (CO_2) cycles. The ocean acts like an organic carbon pump, helping to maintain the climate balance that is now threatened by emissions resulting from human activity. The dissolution of CO_2 in seawater also makes the sea more acidic. The consequences of this have not yet been fully appraised but can already be seen, and there are fears of ecological, economic and social impacts.

Exchanges between the ocean and the atmosphere are also responsible for the formation of water masses and oceanic circulation. The ocean stores solar energy, transports it and returns it to the atmosphere. Ocean currents are generated by the combined action of winds and of the earth's rotation, and are influenced by underwater topography. They move and churn water masses, and are thus pivotal to the climate. Variations in oceanic circulation can therefore engender climate anomalies, such as El Niño events, bringing floods and drought with dramatic consequences for populations. Climate variations are recorded in the sediment deposited on the sea bed, which provides an invaluable archive.

The ocean – the 'cradle of life' – is home to some unique biodiversity, which is still only partially known and which feeds on the nutrients found in seawater.

It plays a vital role in the functioning of marine ecosystems, with some highly original biological interactions. The deep sea comprises a mosaic of habitats specific to each environment. The species found in these areas shrouded in darkness have adapted by replacing photosynthesis with chemosynthesis, which provides alternative sources of energy. Some large animals, such as turtles, have demonstrated their ability to adapt to oceanographic processes.

Finally, the coastal environment – the interface between the continents and the ocean – stands apart because of its physical and biological particularities and its vulnerability. Coasts, estuaries and deltas are subjected to wave action and tides, and anthropological pressure is particularly important, threatening biological communities that once thrived in micro-environments but which are now endangered.

2. Where does the water in the oceans come from?

Pierre Cartigny

The ocean is one of the Earth's main water reservoirs. It is the most obvious, but it is not the only one, and above all, it is not the largest. To understand the origin of seawater, we need to consider the Earth's other major water reservoirs, particularly the mantle (the layer of the globe extending from 5 down to to 2900 kilometres below the surface). The mantle alone is thought to contain double the water of the ocean: an average concentration of around 500 milligrams of water per kilogram of rock. There are huge exchanges between these reservoirs, particularly between the ocean and the mantle, and it is likely that the ocean's size has fluctuated over the geological eras. Two opposing scenarios are currently proposed to explain the origin of this water. In the first scenario, it is considered that terrestrial water came to Earth around 4.4 billion years ago with a 'late veneer' of materials rich in volatile elements (carbon, nitrogen, hydrogen and noble gases). This model argues that the oceans shrank over time, as the Earth's mantle became hydrated, until a stationary state was reached. In the second scenario, the oceans are thought to have formed through the degassing of volatile elements (C, N, H, noble gases) contained in the mantle. This model contrasts the first model, because it states that the oceans grew over time, before reaching a stationary state.

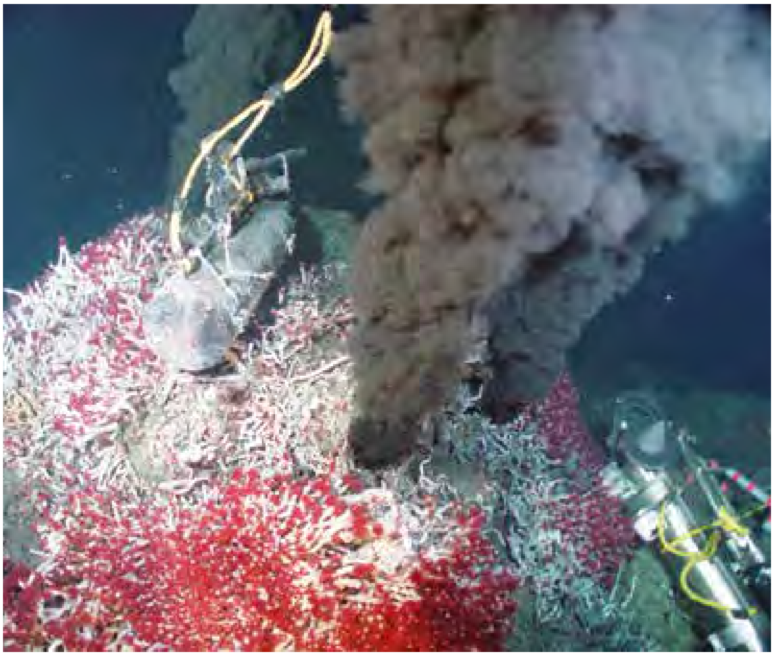
Water exchanges between terrestrial reservoirs

Through volcanism, the Earth's mantle is slowly losing its volatile elements, including water present in the form of hydroxyl groups (OH^-) in certain minerals. Water is concentrated in the magmas. When the pressure drops, these become oversaturated and form gas vesicles. These gases eventually escape, to accumulate in the atmosphere and hydrosphere. The fumaroles and the explosiveness of the volcanoes are both caused by degassing of volatile elements. This process has always existed, and must have been much more vigorous at the time of the Earth's formation, when the mantle was hotter.

Simultaneously, the formation of the oceanic crust on the mid-ocean ridges (cf. II.19) is accompanied by intense hydrothermal activity (interactions between the rock and the seawater). This is manifested at the surface by black smokers, which are a sign of the transfer of essential elements for bio-geochemical cycles (iron, manganese, zinc and copper) towards the surface. Above all, it leads to the formation of hydrated minerals in the crust. One example is serpentine, which is formed from olivine. Water makes up 12% of the weight of serpentine, whereas olivine contains just a few tenths of a milligram per kilogram. The concentration of water in the oceanic crust is therefore multiplied by over 100. Scientists have calculated that in the space of 10 million years, the equivalent of the total volume of the oceans is involved in hydrothermal circulation at mid-ocean ridges. This timescale is long, compared to the flows of evaporation and precipitation, but it is these hydrothermal interactions that control the volume of the oceans in the long term. Without a massive return of water from the oceanic crust to the hydrosphere, all seawater would disappear in under a hundred million years.

This return takes place in subduction zones. As the oceanic crust sinks and the pressure and temperature rise, metamorphic reactions lead to a slow and almost continuous release of water. The high water concentrations of arc volcanoes are an illustration of this, and are one of the reasons why these volcanoes are so dangerous.

However, it is very difficult to evaluate the quantity of water that returns to the mantle. The analysis of hotspot basalts (for example in Hawaii or Réunion), which contain a component of material that has passed *via* the surface, show a decrease in the amount of water compared to basalts from mid-ocean ridges. This suggests that the mantle is losing hydrated elements. However, this idea contradicts the geological hypothesis suggesting that the volume of the oceans has not significantly changed for around 2 billion years. Our knowledge of the mantle's water content therefore remains very poor, and the rare data available suggest variations of up to a factor of 50. In 2014, the discovery of a mineral inclusion in a diamond containing over 1.5% water led Canadian researchers to state that the transition zone (from 410 to 660 km deep) could contain an ocean's worth of dissolved H_20. However, we do not yet understand the mechanism that allows the concentration of so much water. Therefore, all hypotheses are possible, whether this mechanism is internal or connected to subduction. In these circumstances, there is great uncertainty as to whether the Earth's mantle (or the oceans) is (are) losing or gaining water.



A hydrothermal vent (here a 'black smoker') is formed when water (generally hot water) emerges, or more precisely re-emerges, from the depths of the Earth. It starts off as seawater, which is heated deep down by the magma that settles to form the oceanic crust. The seawater re-emerges loaded with (or sometimes depleted of) many elements, making hydrothermal vents very productive and varied biologically. Black smokers are one of the most typical illustrations of exchanges between the solid and liquid parts of our planet. Source: National Oceanic and Atmospheric Administration. ■

The origin of water on Earth

Accessing the composition of 'primordial water' (that of the primitive mantle and/or that which arrived belatedly) is highly problematic, as there as been so much redistribution and mixing of the water between the mantle and the oceans. Consequently, our vision of the origin of water on Earth relies on indirect arguments and is not based on study of the water itself. For example, the geochemistry of noble gases (such as neon and xenon) and of nitrogen gives different isotopic compositions for the mantle and the atmosphere. This suggests the presence of primordial volatile elements (and therefore of water) on Earth, as well as a late input. However, it is still impossible to determine the balance of terrestrial water.

The question of whether the Earth managed to preserve primordial water during its formation is a significant one. Through a phase of melting and crystallization, homogeneous planets become differentiated. For the Earth in particular, the associated formation of the Moon *via* an impact between the proto-Earth and a Mars-sized impactor is an additional argument suggesting that little water could have been preserved. It therefore seems that the Earth's water was input around 4.4 billion years ago by primitive bodies with a high water content, such as chondrites or comets. Based on hydrogen isotope ratios, the hypothesis of a water input from carbonated chondrites (those most like the sun, and which contain up to 20% water in weight terms) seems most likely.

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3. The evolution of the global ocean over geological periods

Yves Lagabrielle

The global ocean as we know it today is the result of a long evolution, largely influenced by the internal dynamics of the Earth. Plate tectonics theory allowed us to understand and quantify the movement of the plates on the Earth's surface. Since the plates carry the continents, through their movements, they also control the shape of the oceans and the average global sea level.

The role of lithospheric tectonics

Very soon after the Earth was formed, a liquid ocean filled the irregularities in its surface. The oldest known marine sediments were discovered in Greenland, and date back to 3.86 billion years ago. Their presence shows that liquid water already existed on the surface of the planet at this time. The composition of the first global ocean differed greatly from that of our current ocean. It had a higher salt content, and contained a large amount of dissolved iron. The Earth was formed by the condensation of a protosolar nebula, 4.5 billion years ago. At first, it cooled quickly, and the external liquid and gaseous envelopes appeared in less than 500 million years, through the degassing of the heavier matter forming the core and mantle. The late collision with interplanetary bodies rich in light elements also contributed to the formation of the primitive hydrosphere and atmosphere.

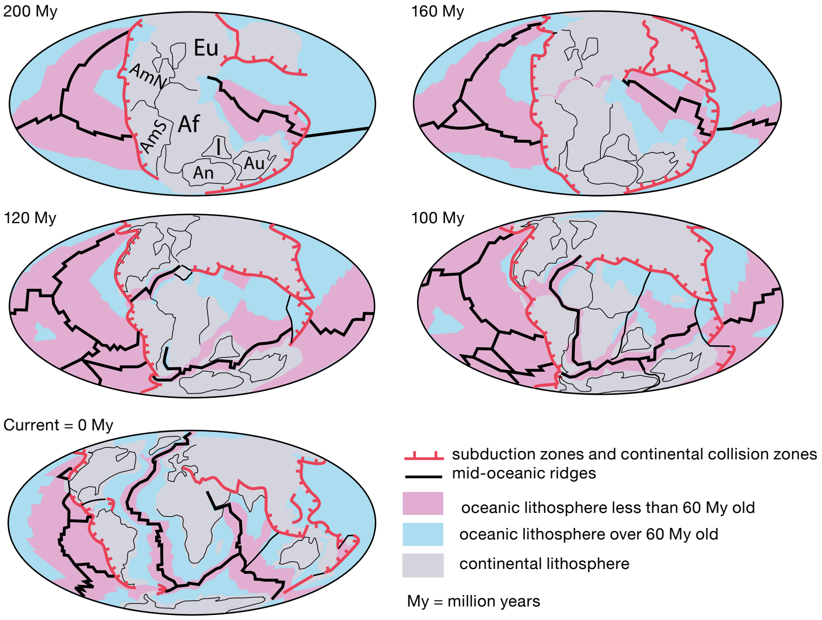
By studying the mountain ranges that form the oldest continents, we can see that before 2.5 billion years ago, the outer envelope of the Earth deformed easily, because its thermal gradient was still high. As it progressively cooled, it became less ductile and stronger. Through this process, the lithosphere appeared 2.5 billion years ago, and with it came the beginnings of plate tectonics. Underneath the lithosphere, vast convection cells trigger movements in the hot but solid mantle, thus evacuating the initial heat and that produced by internal radioactivity. This fundamental stage in the history of the Earth considerably changed its surface, splitting it into several large, rigid, mobile plates on top of this ductile mantle. Consequently, the relief of the Earth's surface is a faithful reflection of the dynamics of the lithosphere.

New lithosphere is created along the axis of mid-ocean ridges, as the mantle cools in the upper part of the ascending limbs of convection cells. It forms vast, flat, slightly sloping regions on either side of the ridges. The old lithosphere returns into the mantle in subduction zones, corresponding to deep, narrow trenches bordering the continents. When two plates collide, they overlap and mountain ranges are formed, for example the Alps, which extend from Gibraltar to the Himalayas.

Gravity forces draw the liquid water of the oceans into the lower parts of the lithospheric relief. Consequently, the oceans are primarily located on the oceanic lithosphere and cover the ridges with an average water depth of 2500 m. They also cover the lowest parts of the continents, forming the continental margins. As soon as plate tectonics began on the Earth's surface, the movements of the lithosphere have been constantly modifying the position and morphology of subduction trenches and ridges. The shape of the global oceanic water reservoir is therefore constantly changing. These modifications are directly reflected by the variations in the average global sea level.

The level, movement and contours of the oceans

Scientists observed the first-order changes in the global average sea level long time ago, well before the emergence of the theory of plate tectonics. Major ocean basin overflows, which are known as marine transgressions and are synchronized on a global scale, are responsible for the very high marine sediment deposits on continental margins. During the Late Cretaceous, from 80 to 70 million years ago, the average global sea level rose to 150 to 250 m higher than it is today. In addition to these major variations, there are smaller variations, which are also synchronous, but are caused by changes in the volume of liquid waters (storage of freshwater in the polar ice sheets, storage of oceanic water in sea ice, ocean warming). Other variations, which are not synchronous on a global scale, produce local changes in the morphology of the oceanic basin, for example due to a rise caused by the collision of two plates in a given region of the globe. These ideas revolutionized the study of all marine sediments: this was the birth of sequence stratigraphy.



Evolution of the lithospheric plates over the last 200 million years. 200 million years ago, a single large plate carried a supercontinent, Pangaea, surrounded by an old single ocean, Panthalassa. Pangaea broke up due to the activity of new mid-oceanic ridges, which produced a young oceanic lithosphere with a high bathymetry. The plates moved apart, the oceanic lithosphere near the continents aged and became deeper, but the ridges produced large amounts of young lithosphere. This led to a progressive change in the global average depth of the oceanic basin, causing seawater to spill over at the continental margins. It has been possible to quantify this change, by integrating an estimate of the bathymetry of the old ocean, Panthalassa. The overflow peaked in the Cretaceous (70-80 million years ago), with the sea level reaching 150 to 250 m higher than its current level. By studying the magnetic anomalies of the oceans, it has been possible to reconstruct plate movements. According to the works of Seton *et al.*, 2012; Coltice *et al.*, 2013; Cogné et Humler, 2006; Cogné, Humler et Courtillot, 2006. ■

The contours of the global ocean are essentially controlled by the movements of the continents, carried by the lithospheric plates. These movements will inevitably bring the continents together into a single supercontinent, in less than 300 million years. In such an arrangement, the Earth will have a continental face on one side and a marine face on the other, forming a single ocean. In the lithospheric cycle (Wilson cycle), a supercontinent invariably fragments again. New plates break off, then progressively move apart as new oceans open up. The new continents are thus separated by very young oceans. They spread out, and in front of them, the old oceanic lithosphere is resorbed, disappearing through the process of subduction. The floor of these young oceans is higher than that of the old ocean, so the global average ocean depth is proportionally lower. A major transgression follows, as sea water floods over the continental margins. Very recent studies of the magnetic anomalies of the ocean floor have allowed us to reconstitute the evolution of young ridges over the last 200 million years in great detail. As such, scientists have been able to calculate the variations in the morphology of the ocean floor over this period, and show the coincidence between the peak of the last major transgression in the Cretaceous (80–70 My) and the period when the global ocean was at its lowest depth during the last Wilson cycle.

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4. The origins of life

Marie-Christine Maurel

Since the formation of the Earth, 90% of the history of life has taken place in the oceans, thanks to their reserve of oxygen, used by all living beings. Water (H_2O) is present everywhere in the universe: as a gas (clouds, vapour), in the atmosphere and in space; and as a solid in the form of comets (frozen water) and on Earth (icebergs). However, liquid water is rare, and the Earth is the only planet in our solar system where it exists in large amounts. It is thought that there was once a single ocean, Panthalassa, which existed from the end of the Palaeozoic and surrounded Pangaea, the super-continent formed around 550 million years ago (Fig. 1).

The birth of the oceans

In 1871, Charles Darwin declared, '*But if (and Oh! what a big if!) we could conceive in some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity..., present, that a protein compound was chemically formed ready to undergo still more complex changes, at the present day such matter would be instantly devoured or absorbed, which would not have been the case before living creatures were formed.*' Thus, the founder of the theory of evolution was already considering the problem of the chemical transformation and evolution of mineral molecules into organic molecules in an aqueous medium. Today, in the laboratory, research teams studying the origins of life simulate the birth of life in water. Some mimic the conditions of deep-sea hot springs 3000 m beneath the surface, whilst others prefer to alternate periods of drought and hydration in hydrothermal sites on the surface (Fig. 2), or to interact clays or iron sulphides with water. For scientists, the only certainty is that water was indispensable to the emergence of life, whatever the exact nature of the environment.

Thanks to the isotope analysis of oxygen-18 (^{18}O) and oxygen-16 (^{16}O) extracted from zircon ($ZrSiO_4$: the oldest currently known mineral, of which crystals dating back 4.4 billion years have been found in Australia) we know that the Earth already had one or more liquid water oceans at that time. Following the degassing of the crust and mantle during the Hadean, volcanoes on planet Earth expelled large quantities of water vapour. Through condensation and precipitation (estimated at 4 metres per year), this created the oceans. Undoubtedly, this accumulated quantity of water would not have been enough without the considerable contribution from the heavy comet and meteorite bombardment which lasted for hundreds of millions of years. Comets, these 'bearers of water', asteroids and water-rich meteorites brought large volumes of water to our planet.

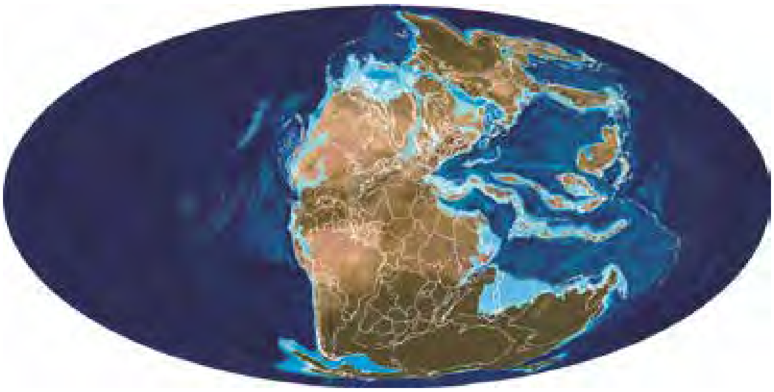

Fig. 1 – Today's international borders and coasts superimposed on Pangaea as it was 250 million years ago. The ocean around Pangaea is Panthalassa. © J. N. COOKSON / NGM. ■

The history of the oceans, recorded in sedimentary rocks, allows us to determine the temperature of this water around 3.5 billion years ago, during the Precambrian. The isotopic compositions of the oxygen and silicon in old flints suggest that the primitive ocean was very hot, reaching temperatures of up to 80°C.

Moreover, unlike the oceans today, which are slightly basic (around pH 8), the first oceans had a lower pH, because of the high level of CO_2. Very acidic or very basic conditions, such as those seen near hydrothermal vents, allowed the first prebiotic reactions to occur.

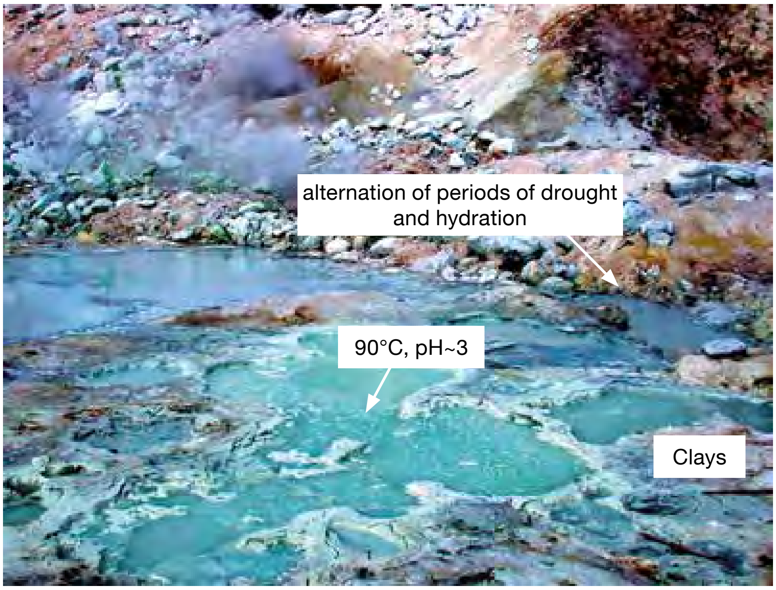

Fig. 2 – **Hydrothermal vents on Mount Lassen in northern California.** Source: D. DEAMER, Life, 2017. ■

The birth of life

In the 1920s, Alexandre Oparine and John Haldane proposed the scenario of the 'primitive ocean', a sort of 'prebiotic soup' in which organic molecules settled. These molecules were formed in a reducing atmosphere and brought to the planet by the many heavy rains. The molecules in question: methane (CH_4), ammonia (NH_3), water (H_2O) and hydrogen (H_2), are thought to have reacted in the primitive ocean to form simple molecules, hydrogen cyanide (HCN, formed by the combination of methane and ammonia) and formaldehyde (HCHO, a product of the reaction between water and methane). This mixture, benefiting from a supply of thermal, electrical (lightning) or photon energy (solar UV), gradually evolved to create the building blocks of life and the vesicles (coacervates), the first 'ecological niches' able to concentrate and bring together prebiotic reactants. Stanley Miller tested this formidable hypothesis in the laboratory of Harold Urey (who won the Nobel Chemistry Prize in 1934). In 1953, Miller successfully produced the prebiotic synthesis of five amino acids, completely identical to the amino acids in our living cells. Amino acids are the building blocks of proteins that are essential for structural, enzymatic, hormonal, immune and other functions). In the 1960s, Juan Oro managed to combine five HCN molecules and obtained, in a prebiotic soup, the nitrogenous bases of our nucleic acids, DNA (deoxyribonucleic acid) and RNA (ribonucleic acid), the molecular components of chromosomes. In these conditions, the main synthesis route generates adenine that is part of RNA and DNA, but also of coenzymes and ATP (adenosine triphosphate), the energy exchange currency of all living cells.

Finally, the search for extraterrestrial life is essentially focused on zones where there is liquid water (or evidence that it was once present). This is the case of the planet Mars, and for the search of signatures of life in the deep oceans of Enceladus and Europa (satellites of the giant planets Saturn and Jupiter, respectively) and on the exoplanets.

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5. The first life on land

Philippe Janvier

The anteriority of aquatic, generally marine species relative to terrestrial species is now proven, thanks to phylogenetics, comparative biology and the study of fossils. The processes of adaptation by which organisms moved from the aquatic to the terrestrial environment are highly diverse, and there were several independent emergences onto land (or 'terrestrializations'), favoured by the increased rate of atmospheric oxygen from around 800 million years ago (My), due to photosynthesis. The first to leave the sea were the embryophytes (land plants), arthropods, molluscs and vertebrates. The fossils of these organisms document their anatomical adaptations.

Plant terrestrialization

For these first colonizers of the land, the main challenges were gravity, respiration, retaining and circulating water, locomotion (for animals) and protection against ultraviolet rays. The different terrestrializations also raise the question of a transition through a fresh water stage versus a direct passage from marine to terrestrial life. In some cases, the distinction between aquatic and terrestrial organisms is unclear, because organs considered characteristic of life on land are often exaptations: recruitments of structures that were already perfectly functional in their water-dwelling ancestors.

There were already terrestrial or freshwater micro-ecosystems containing single-cell or multicellular bacteria and eukaryotes (algae, fungi) around 1 to 1.2 million years ago. However, it was around 500–470 My that the first traces of lichens, fungi and perhaps terrestrial embryophytes appeared. Around 420-410 My, several plants displayed characteristics unique to embryophytes (spores, cuticle, stomata) and some had water-conducting tissue. It is thought that they resembled small thorny twigs, 5–10 cm long, with sporangia. However, very quickly, large monilophytes (ferns and horsetails) appeared, needing damp ground to reproduce. Then came lignophytes (woody plants), including spermatophytes (seed-producing plants), which had already reached 30 m high 360 million years ago. In nature today, there are still representatives of most of the large embryophyte groups that participated in plant terrestrialization, allowing us to understand the place of fossils in their evolution. The closest aquatic relatives of embryophytes are thought to be charophytes or coleochaetales: freshwater green algae, which like embryophytes are classified as streptophytes. The terrestrialization of embryophytes is thought to have been favoured

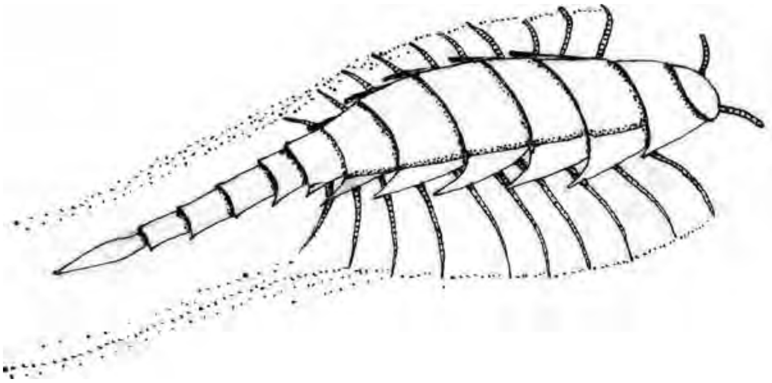

Fig. 1 – *Euthycarcinoidea*, which were among the first arthropods to adapt to life on land, lived almost 500 million years ago. The precursors of millipedes, they left trails on the beaches of the Cambrian Period, thus showing their adaptation to aerobic life (out of water). © P. JANVIER. ■

by segregation, around 550 My, between marine green algae and the first freshwater streptophytes trapped in coastal lagoons.

Animal terrestrialization

In the animal kingdom, terrestrializations occurred in a piecemeal fashion, with many groups remaining dependent on the aquatic environment for part of their life cycle (such as crustaceans and amphibians). Only amniote vertebrates (reptiles, birds and mammals) and certain and arthropods (insects, spiders, scorpions and millipedes), annelids (earthworms) and gastropods (snails) truly broke their ties with the aquatic environment. The date of their terrestrialization can be estimated using fossils found in terrestrial and freshwater sediments, or fossils that present anatomical characteristics connected to aerobic life (spiracles, tracheas, lungs, locomotor appendages) with a known function in their current terrestrial relatives. It can also be deduced from the molecular phylogenics of extant marine and terrestrial species, calibrated over time (molecular clocks), which allow us to date their divergences. Using this method, we can infer the habitat of the last common ancestor of a monophyletic group. Unlike that of embryophytes, the phylogenetic tree of today's animals contains many gaps, due to extinctions of groups that might have provided information on the adaptive transitions partly documented by fossils. For example, the transition between fish and terrestrial vertebrates with limbs and digits (tetrapods) is only documented in nature today by coelacanths, lungfish and modern amphibians. However, fuller information can be gleaned from the many fossil lobe-finned fishes and tetrapods from 400-360 My. These allow us to date the stages of the appearance of choanae (internal nostrils) or locomotor limbs, which were decisive for their adaptation to life on land.

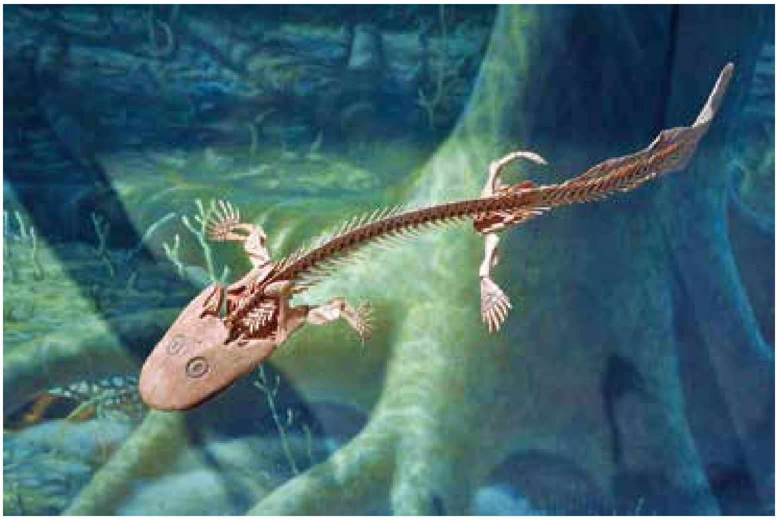

Fig. 2 – **Skeletal reconstruction of the labyrinthodont *Acanthostega gunnari*, one of the earliest limbed vertebrates.** On display at the American Museum of natural History. ■

The molecular clocks of arthropods (insects, collembola, crustaceans, myriapods and arachnids) suggest earlier dates of divergence than fossil data for terrestrial groups (myriapods: 528 My, hexapods: 468 My), but it is unlikely that there were any truly terrestrial species before 500 My. The oldest terrestrial myriapods and arachnids with respiratory spiracles can be traced back to 425 to 410 My, but their older stem groups were marine-dwelling. There is evidence of terrestrial ecosystems containing vascular plants, fungi and various arthropods (mites, arachnids, myriapods and hexapods) from around 400–415 My. The adaptation of gastropod molluscs to the terrestrial environment occurred independently nine times, *via* different methods from 360 My onwards. Some came from marine ancestors and others from freshwater ancestors. Among vertebrates, the stages in the evolutionary transition from the simple capacity for temporary aerial respiration to clear terrestrial locomotion took place from 390 to 340 My. The oldest tetrapods lived in coastal marine environments, but from 370 My, they populated coastal lagoons, estuaries and temporary lakes.

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6. Seawater: a chemical solution

Catherine Jeandel

The ocean is a vast chemical solution. It contains variable concentrations of all the elements in the periodic table, as well as artificial compounds, such as pesticides or medical derivatives. The ocean's chemical composition reflects the balance between element inflows and outflows, and it changes according to the rhythms of these flows. This affects the ocean's capacity to trap carbonic gas: it is therefore essential to understand how the system works.

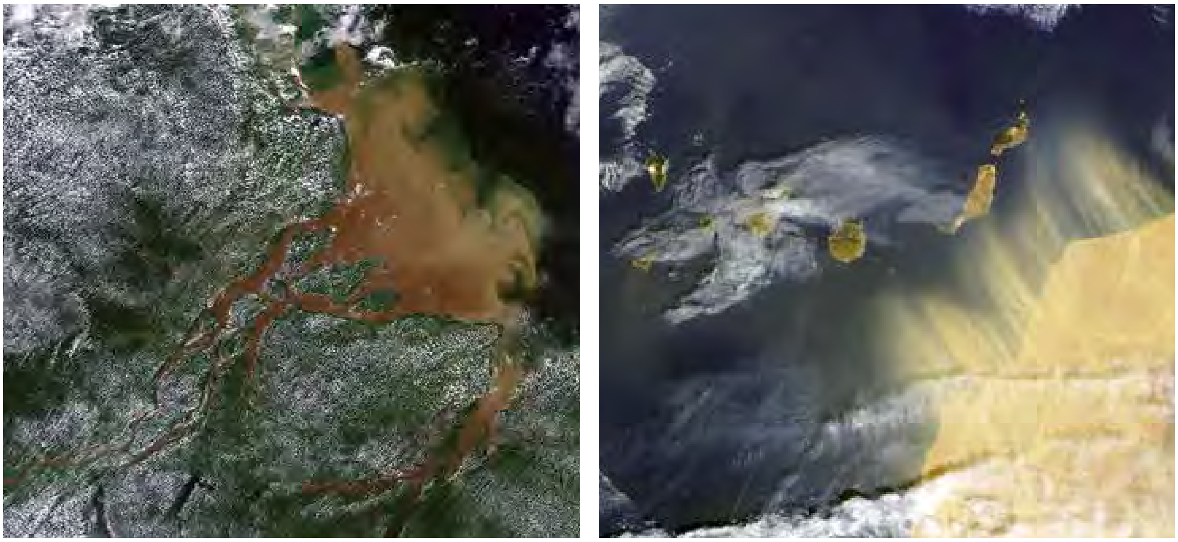
The chemical composition of the ocean

When they dissolve, salts release their ions. For example sodium chloride (NaCl) releases Na^+ and Cl^-. Just six ions make up 99% of chemical species in the ocean: the sodium ion Na^+, the chloride ion Cl^-, the magnesium ion Mg^{2+}, the sulphate ion SO_4^{2-}, the calcium ion Ca^{2+} and the potassium ion K^+. The concentration of these chemical species (which is measured in millimoles per litre, 10^{-3} mole/L) varies only very slightly from one side of the ocean to the other. However, it is vital to precisely determine the 'salinity' of the ocean, because even the slightest variation alters the density of the water (cf. II.11).

Nutrients are less abundant, but essential for the growth of algae, which assimilate them and use the sun's energy to transform these dissolved elements into organic and mineral matter. The 'organic' part of cells is made up of nitrate (N), phosphate (P) and carbon (C), while their skeletons are formed of silicon (Si) and calcium (Ca). The abundance of these elements (which is measured in micromoles per litre, 10^{-6} mole/L) varies considerably between the surface and the seabed, and from one side of the ocean to the other. Biological activity extracts them at the surface, resulting in extreme depletion. When organisms die, bacteria return these elements to the solution. Their concentration is therefore higher in deeper waters, because this dissolution occurs mainly in the deep oceans. Moreover, the deep waters circulate and age between the Atlantic Ocean and the Pacific Ocean (cf. II.11), so they acquire more nutrients during transit. Thus, the nitrate concentration is close to 0 µmol/L at the surface of the Atlantic, compared to 18 µmol/L in the deep waters of this ocean and it is over 40 µmol/L in the deep Pacific Ocean.

More recently, it has been shown that other elements are essential for life, because they are present in the enzymatic reactions of photosynthesis and respiration. Thus, the development of all species is dependent on iron, copper, zinc, cobalt and cadmium, which are now considered as essential nutrients too. There are trace amounts of these elements in the ocean (nanomoles per litre, 10^{-9} mole/L), but they are very abundant on the continents… and in rust on ships! To detect them, they need to be collected using special bottles, working under ultra-filtered air and in dedicated rooms. Recent analytical advances allow an increasingly documented mapping of these elements, particularly thanks to the global effort as part of the GEOTRACES programme.

Even scarcer elements are excellent tracers for studying this complex marine system. Some are comparable to 'dyes', because they provide information about the origin of water masses or dusts which reach the sea's surface, then settle at the bottom of the ocean. Others are natural radioactive elements, such as thorium or radium. They act as temporal markers to determine when



Left: satellite view of the mouth of the Amazon, showing deposits of fluvial matter. © Météo France. **Right: cloud of Saharan dust over the Canary Islands.** © Terra / MODIS. ■

water left the shore, or the speed at which matter is descending towards the depths. The abundance of these elements varies from picomoles per litre (10^{-12} mole/L) to femtomoles per litre (10^{-15} mole/L), for radionuclides. One of them (actinium 227), which is very useful in deep waters, is present at a concentration of 10^{-18} moles (also called 'atomole') per litre! Although these elements are very difficult to detect analytically as underlined above, their tracer properties make them key parameters to be measured. Finally, gases, such as oxygen (cf. II.8) and carbonic gas (cf. II.9), are also present in the ocean.

Chemical element sources and sinks

Most of the chemical elements are produced by the weathering of continents. For some, such as iron and zinc, a significant fraction may come from deep-sea hydrothermal vents (cf. II.19). Those coming from the continents are mainly carried by winds and rivers. In areas off deserts, winds carry dust which is rich in iron, silica and phosphates. These partially dissolve on contact with the surface, stimulating biological activity. However, these inputs are temporally and spatially sporadic, and around 50 times lower than those discharged by rivers. River inputs are either dissolved (solution) or solid (suspended eroded matter). For a long time, scientists thought that this solid matter was deposited in the mouths of rivers and stopped reacting. However, measurement of the tracers described above has shown that deposited sediments actually release a small fraction of their contents. Given that they are very abundant, this represents a large flux of elements. This has revolutionized our understanding of the iron cycle. Whereas in the early 2000s, winds were considered major carriers of iron the dissolution of marine sediments and hydrothermal inputs are now regarded as dominant (cf. II.19).

The elements leave the marine system after a certain time (called the 'residence time'), which varies according to their reactivity (soluble or insoluble) and their role (in life cycles or not). This departure occurs *via* sedimenting particles. They may come from life at the surface, from the spontaneous precipitation of iron oxides (a sort of marine rust), or from adsorption on fine particles which fall slowly towards the sediments. Poorly soluble elements (like aluminium) stay for less than 50 years, whereas more soluble elements (like silica or sodium) may remain for several thousand or several million years.

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7. The colour of water

Frédéric Partensky and Laurence Garczarek

As described by J-L. Soret and W. Spring as early as the end of the 19th century, the color of pure water, and particularly seawater, is blue. However, the color of the sea varies considerably depending on its load of suspended particles (Fig. 1). Thus, estuarine waters that are heavily laden with mineral particles (mud, silt, sand) and colored dissolved organic matter appear to be brown, coastal or upwelling waters that are rich in nutrients favoring phytoplankton growth appear to be green, while nutrient-poor offshore waters, are mostly blue. More rarely observed, the poorest of the world's oceans located west of Easter Island in the South Pacific Ocean, and whose exceptional transparency allows ultraviolet radiation to penetrate several meters below the surface, appear to be blue-violet. Although the reflection of the sky modifies the apparent color of the sea water, its influence is limited. Similarly, the color of the seabed may alter the apparent color of the water, but only if the depth of the water column is shallower than the sunlit layer. Hence, the inimitable color of lagoons is conferred by underlying white coral sands.

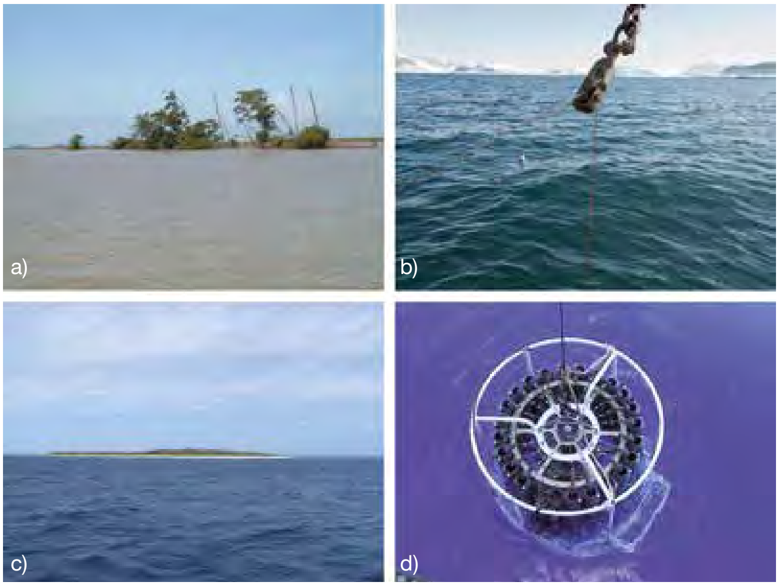

Fig. 1 – **Variations in water color depending on the concentration of mineral or phytoplankton particles.** a) Brown water at the mouth of the Kaw River, French Guiana. © A. VAQUER / CNRS Photo library. b) Green water of the Kongsfjorden Fjord, Norway. © E. AMICE / CNRS Photo library. c) Blue ocean waters off Surprise Island, South Pacific Ocean. © J.-L. CHAPUIS / MNHN / CNRS Photo library. d) Blue-violet water in the core of the South Pacific gyre. © J. RAS / CNRS Photo library. ■

The sea, a colored filter

When sunlight reaches the surface of the ocean, it is white, as it is the sum of all visible colors. Its multicolored spectrum can be admired during rainbows, a phenomenon resulting from the diffraction of white light by raindrops. Sea water acts as a color filter that gradually absorbs the different colors as the sunlight penetrates deeper into the water column. The first wavelengths to be absorbed are those at the edge of the visible light spectrum that our eyes cannot see, infrared and ultraviolet radiation. Next red, orange, purple, yellow and green (in that order) are absorbed, while blue penetrates the deepest. This phenomenon of progressive attenuation explains the apparent monochromy of the underwater environment during deep diving; only the white light of spotlights can give algae or fishes their bright natural colors back.

From outside, the color of the sea perceived either by our eyes or by satellite sensors corresponds to the photons reflected by the surface of the water, *i.e.* those not absorbed by seawater. This 'reflectance' translates the optical properties of the underlying marine waters and, in offshore waters, is proportional to the concentration of phytoplankton in the water. Hence, reflectance measurements made by satellite-borne spectroradiometers (such as SeaWiFS, MERIS MODIS or VIIRS) can be converted into chlorophyll concentrations using mathematical models, making it possible to obtain maps of phytoplankton biomass distribution at the global ocean scale.

Fig. 2 – **Culture flasks containing the marine cyanobacterium *Synechococcus* illustrating the wide range of pigments in this genus.** © L. GARCZAREK. ■

Adaptation of marine phytoplankton

Chlorophyll *a* is the main pigment in the vast majority of phytoplankton organisms. It plays a central role in photosynthesis because it is a particular form of this pigment that converts solar photons into chemical energy, which can be used by the cells. The others, called 'accessory pigments', may be either other forms of chlorophyll, or carotenoids or phycobiliproteins. Some of them are used to capture solar photons of various wavelengths, while others protect the photosynthetic apparatus from the harmful effects of excess light. This photosynthetic pigment suite is highly specific to each group of phytoplankton, and their combination confers specific absorption properties to the cells, enabling them to preferentially capture certain colors rather than others. Some groups, including *Synechococcus cyanobacteria*, display a very wide range of pigments (Fig. 2), enabling cells to capture the dominant color in their environment. Most *Synechococcus* cells have a fixed pigmentation, with maximum absorption of accessory pigments in the orange, red, green or blue parts of the visible light spectrum, a specialization that limits them to particular spectral niches: estuaries, coastal waters and the open ocean, respectively. Other *Synechococcus* cells are like chameleons, capable (within a few days) of changing their pigmentation to preferentially capture either blue or green, depending on the dominant color of the ambient seawater. This ability, called 'chromatic acclimation', appears to be transmitted between *Synechococcus* cells by horizontal gene transfer. This physiological plasticity allows them to continue to grow optimally, even when currents or vertical mixing drag them into a very different light environment.

In conclusion, the color of the sea is not just an inexhaustible source of inspiration for painters and novelists, but is also an invaluable source of information for oceanographers who, through the 'eyes' of satellites, have access to an overall view of phytoplankton distribution in the ocean. Moreover, for phytoplankton organisms, color is a key environmental factor to which they must adapt, much like they do with temperature or nutrient availability.

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8. Oxygen and the ocean

Aurélien Paulmier

Oxygen (O) is the most common atom on our planet, particularly in the air, in the oceans in the form of water (H_2O), and in the molecules of all living organisms. For the last 2.8 billion years, cyanobacteria and algae in the oceans, and plants on the continents, have been using solar energy for their photosynthesis, thereby allowing the formation of oxygen (O_2), of which the Earth was largely deprived at its origin. The concentration of O_2 in the atmosphere is high (20.8%), and is directly linked to life, which is a chemical aberration compared to O_2 rate on other planets. This gaseous molecule, in dissolved form in aquatic environments, is also a powerful oxidant, able to form compounds with almost all other chemical elements. The appearance of O_2, a waste product of photosynthesis, was a disaster for primitive living organisms, and was the cause of mass mortality until the emergence of breathing or respiratory functions. Breathing O_2 then became vital for all aerobic species: bacteria, plants, and animals. Paradoxically, O_2 also produces free radicals that damage biological molecules and cells, causing mutations and ultimately, death. Consequently, the level of oxygenation, which is relatively stable in the atmosphere, plays a key role in the regulation of life. In return, living organisms control the rate of O_2 through mechanisms that produce oxygen, photosynthesis, and consume oxygen, respiration / remineralization.

The role of the ocean

The oxygen cycle is based on exchanges between compartments, primarily the atmosphere and the oceans, since at least 50% of the oxygen we breathe comes from the ocean. Atmospheric O_2 penetrates the ocean at the poles and is released at the equator. Seasonally, the ocean absorbs O_2 in autumn and winter, and degasses it to the atmosphere in spring and summer. These transfers are explained on the one hand by physical-chemical mechanisms, since O_2 is more soluble in cold conditions, and on the other hand, by biologically-related episodes of phytoplankton blooms and their degradation.

The ocean is oxygenated in the sunlit layer that is in contact with the atmosphere, and is mixed by wind and waves. This is the layer where most marine photosynthesis takes place, but below this layer, the concentration of O_2 tends to decrease with depth. Near the poles, salty cold waters resulting from the formation of sea ice, sink to the bottom (> 4,000 m), enriched in O_2. These deep waters circulate from the northern and southern Atlantic Ocean to the Indian Ocean, and then to the North Pacific, where they upwell after a journey lasting around1,000 years, representing the major oxygenation mechanism in the ocean (cf. II.11). Along the way, driven by current modulation, these

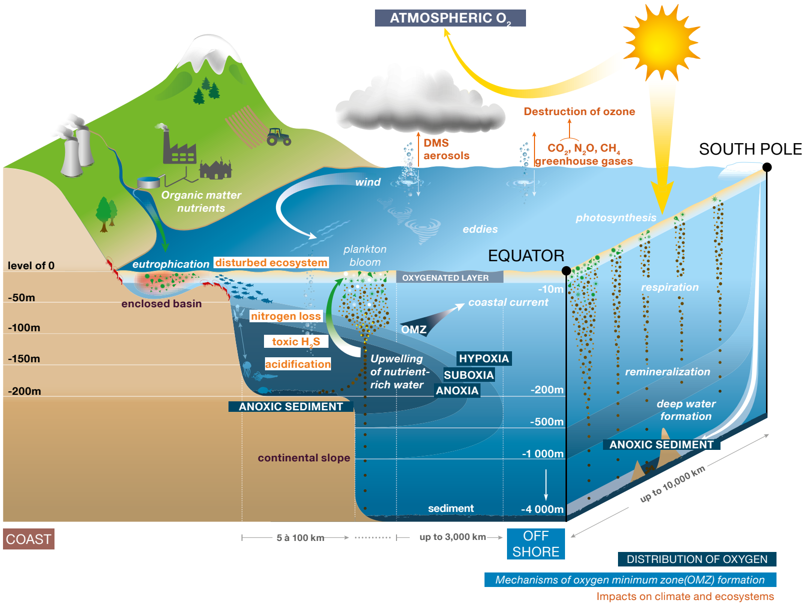

Fig. 1 – **Distribution of oxygen (O_2) and OMZs in the ocean (blue) with their main associated mechanisms (white) and areas of impact (orange), at the large offshore scale (on the right) and at a smaller scale near the coast (on the left).** © M. P. CHARRIA and A. PAULMIER. ■

waters gradually lose their O_2. They are exposed to a rain of particles produced in the surface layer by phytoplankton and by the trophic network, which when degraded, consumes O_2 during the process of remineralization. As a result, the rate of dissolved O_2 can be used to reconstruct the history of a water mass and as a tracer of its evolution. Remineralization mainly occurs between the surface and a depth of 1,000 m, caused by microbial communities that can travel attached to particles, thereby creating an O_2 minimum in intermediate ocean waters (Fig. 1).

In the most sluggish waters, which are relatively old since they have not been in contact with the atmosphere for between10 and 100 years, the O_2 minimum may intensify (suboxia, anoxia). Often outlined by eddies, these waters form the oxygen minimum zone (OMZ), reaching from about 10 to 1,000 m depth and extending up to 3,000 km from the continental margins in the open ocean like in the eastern Pacific Ocean, or in more closed configurations (*e.g.* North Indian Ocean, Black Sea, deep trenches, estuaries, for instance, Fig. 2).

Evolution and impacts on climate and ecosystems

In response to climate variations, periods of oxygenation in the ocean naturally alternated with periods of deoxygenation: from geological time-scales (~million years) to hourly fluctuations. These complex changes result from ventilation and ocean mixing processes, but also from the production of planktonic particles occasionally fertilized by upwelling. However, since the industrial revolution, and especially since the end of World War II, global warming has led to warmer surface temperatures and,as a direct consequence, oceans tend to deoxygenate more. In coastal areas, where sediments play an important role in remineralization, the frequency at which hypoxic events are recorded has increased exponentially in response to effluent discharges. However, the roles of both natural and anthropic causes still need to be better understood.

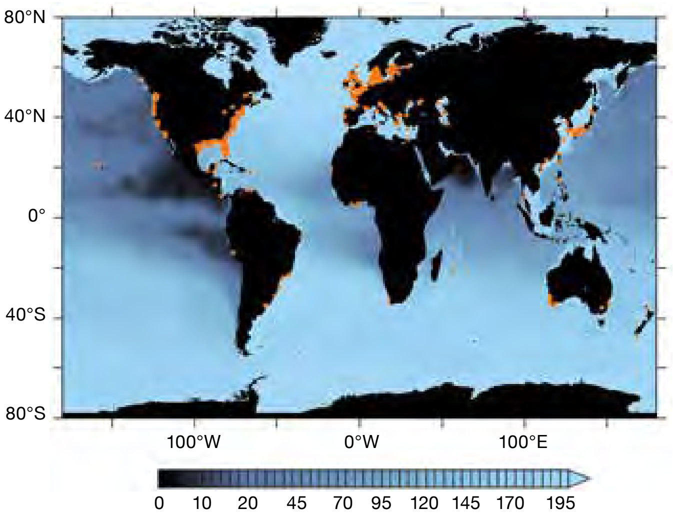

Fig. 2 – **Distribution of areas of oxygen minimum concentration (O_2) in the ocean (µmol/liter). Oxygen minimum zones (OMZs) in dark blue-gray shading. Coastal sites where hypoxic events have been reported are in orange.** Data from the World Ocean Atlas 2013 and Diaz and Rosenberg, 2008. © A. PAULMIER and S. ILLIG. ■

To conclude, let us emphasize the importance of the oxygen minimum zones (OMZs), given their potentially major feedback to the Earth's biogeochemical cycles impacting the climate: source of greenhouse gases, destruction of stratospheric ozone, role in the formation of clouds *via* marine aerosols, and regulation of albedo. OMZs, which have long been classified as dead zones, also have an impact on ecosystems and fisheries *via* the respiratory barrier, nutrient losses (nitrate), acidification, production of toxic gases, and limitation of biodiversity. OMZs are natural laboratories to study how life adapts to climate change, as they are refuges for unsuspected marine life, favoring the emergence of ecosystems that are among the most active and abundant of the ocean in the transition zone between oxygenated and deoxygenated environments. We must therefore be vigilant and maintain a stable balance in oxygen dynamics between the various compartments of our planet and the ocean, in full interaction with the different forms of living organisms.

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9. Ocean acidification

Jean-Pierre Gattuso and Lina Hansson

Climate change and global warming, due to the increase in the greenhouse effect, are now well known to all, and it is widely acknowledged that human activities, including their emissions of carbon dioxide (CO_2) are the main cause. Ocean acidification, on the other hand, remains practically unknown, as its magnitude and its consequences have only recently been discovered. However, carbon dioxide is also responsible for ocean acidification which is consequently is sometimes referred to as ‘the other CO_2 problem’.

A chemical phenomenon

All the CO_2 we produce does not remain in the atmosphere. About a quarter of the CO_2 emitted, about 26 million tons, is absorbed by the oceans every day. Without the oceans, the amount of CO_2 in the atmosphere would be much greater, as would global warming and climate change. Before the 2000s, scientists thought that the absorption of CO_2 would have no significant effect on the oceans or on the organisms that live in them. However, the dissolution of CO_2 in seawater causes chemical changes: a decrease in pH (corresponding to an increase in acidity) and in the amount of carbonate ions.

Ocean acidity has increased by 30% (the pH decreased from 8.2 to 8.1), in the last 250 years *i.e.* since the beginning of the industrial revolution. Future changes in pH will depend on CO_2 emissions. Simulations have shown that, at current rates, the acidity of surface water could triple by the end of the century. Current absorption of CO_2 is 100 times faster than it has occurred naturally over the last 300 million years.

Impacts on organisms

The impacts of acidification are either neutral or negative or, more rarely, beneficial. When CO_2 dissolves in seawater, it increases protons (H^+ ions) but reduces certain molecules, such as carbonate ions, which many marine organisms (corals, mussels,

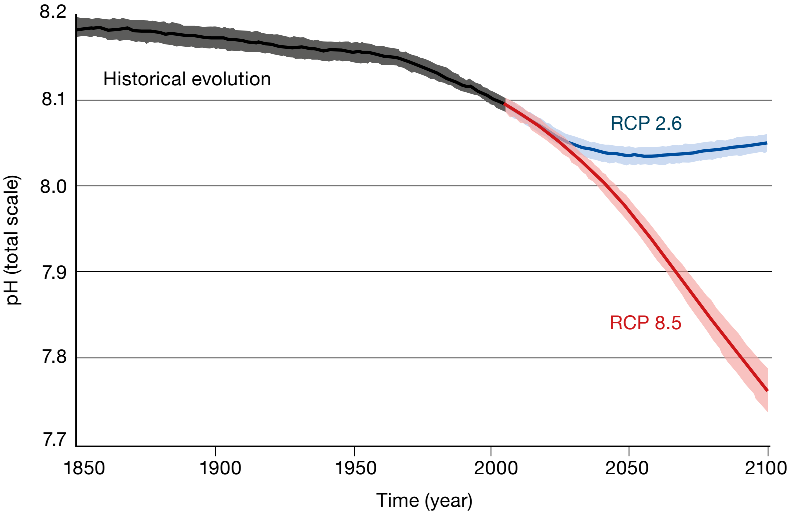

Fig. 2 – **Change in pH since the beginning of the industrial revolution.** RCP 2.6 scenario is "low CO_2 emissions" consistent with the objectives of the Paris Agreement. RCP 8.5 scenario is "high CO_2 emissions", the path we are currently on. Source: J.-P. GATTUSO *et al.*, 2015 ■

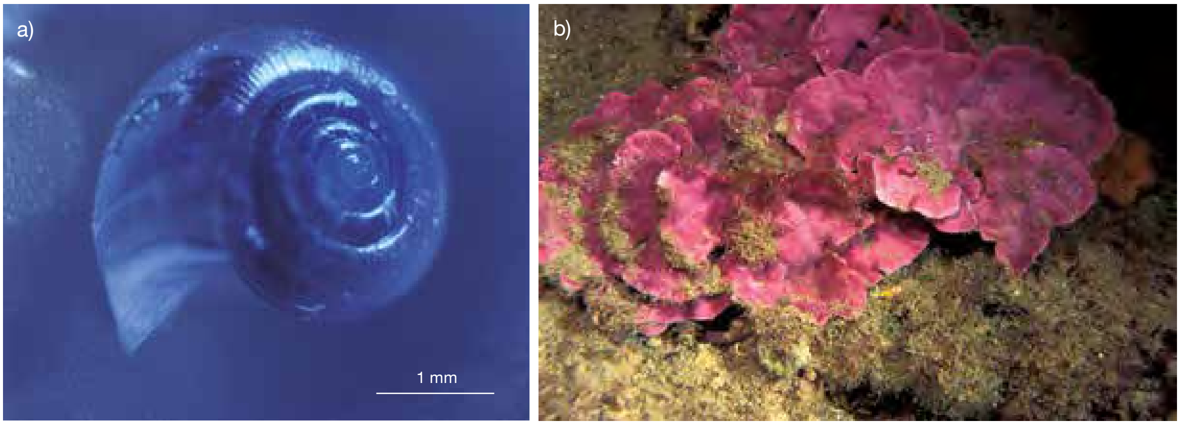

Fig. 1 – **a) This small sea snail (*Limacina helicina*) plays an important role in the food chain and in the functioning of Arctic marine ecosystems.** © S. COMEAU / LOV-CNRS-UPMC. **b) Mediterranean calcareous algae, which is adversely affected by ocean acidification.** © D. LUQUET / OOV-CNRS-UPMC. ■

oysters...) need to produce their limestone skeleton or shell. These plants and animals will thus have increasing difficulties producing these structures. Their skeletons and shells are also threatened with dissolution. Indeed, above a certain threshold of acidity, sea water becomes corrosive to limestone. Adverse effects have already been observed in some species, *e.g.* in pteropods and calcareous algae (Fig. 1).

The effect of ocean acidification on biodiversity is also negative. On the one hand, biodiversity around natural sources of CO_2 is much lower than that a few hundred meters from these sources. On the other hand, all mass extinctions that have taken place in the geological history of the oceans have occurred during marked episodes of acidification (due to volcanic activity or methane emissions). These episodes were accompanied by warming and decreasing oxygen availability, and this cocktail closely resembles what is expected in the future.

The beneficial effects mainly concern certain algae and plants, as photosynthesis and nitrogen fixation can be stimulated by the increased availability of CO_2.

Impacts on society

Oceans acidification can have direct effects on the organisms we consume, such as mussels and oysters, which need calcium carbonate for their shells. In addition, negative effects on zooplankton, such as those observed on pteropods, could also have consequences for human society. Everything in the ocean is interconnected and many organisms depend, for example, on plankton or corals as a source of food or habitat. Thus, acidification could have an impact on the food chain and biodiversity of certain ecosystems. For example, pteropods are consumed by salmon in the North Pacific and Arctic Ocean, and their predicted disappearance would disorganize the fishing of these salmon resources.

The only proven, safe, and effective, method to control ocean acidification is to reduce CO_2 emissions. If emissions continue to increase at the same pace as in recent years, it would lead to a decrease in pH of 0.43 units (a 170% increase in acidity) by 2100. A reduction in CO_2 emissions compatible with the Paris Agreement would limit this decrease to 0.14 units (+40% acidity). The full implementation of the Paris Climate Agreement, signed in 2015, would therefore enable a gradual halt of ocean acidification, but it will take several hundred years to recover the same seawater chemistry as prevailed in the 19th century (Fig. 2).

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10. Ocean-atmosphere exchanges and water mass formation

Michèle Fieux, Gilles Reverdin, Sabrina Speich and Pascale Delecluse

The ocean covers 71% of the Earth's surface and represents more than 96% of the Earth's free water. The ocean-atmosphere fluid ensemble is an immense thermal machine fueled by the sun, and its two components interact continuously. With an average depth of 3,800 meters, the ocean is an immense heat reservoir and represents the 'thermal flywheel' of this ocean-atmosphere ensemble.

A thermal machine...

Solar radiation at the surface of the Earth is not uniform: it decreases from the equator to the poles, because of its inclination with latitude, causing an excess of heat in the ocean's equatorial and tropical regions. This imbalance induces an average meridional ocean circulation that carries heat from the equator poleward. The heat stored in the equatorial oceans is then returned to the atmosphere. Part is lost through radiation and a part, of the same order of magnitude, by evaporation (Fig. 1). These heat and water losses have significant consequences, particularly for deep-ocean circulation. But they also affect the distribution of heat and water vapor in the atmosphere, which is heated by its 'oceanic floor'. They thus influence the distribution of high and low pressure systems and, consequently, the winds that occur between. In turn, these winds transfer mechanical energy to the ocean and drive ocean currents that transport thermal energy accumulated in the tropics to medium and high latitudes. There are continual exchanges of heat, water, and movement between the atmosphere and the ocean, which are always in search of balance.

Overall, the ocean receives almost as much heat and water as it exports. However, regions of gain and loss of thermal energy (by radiation, conduction, or evaporation) or of water (by precipitation, runoff, evaporation, freezing or ice melting) are not distributed evenly. By reducing the density of surface water, gains of fresh water and heating have a stabilizing effect. The ocean is heated from above, resulting in particularly strong thermal stratification in the surface layers. This region of maximum vertical thermal gradient is called the 'thermocline'. Conversely, cooling and loss of fresh water (by evaporation or freezing), under the effect of cold and dry winds, increase surface density, causing vertical movements that penetrate more or less deeply.

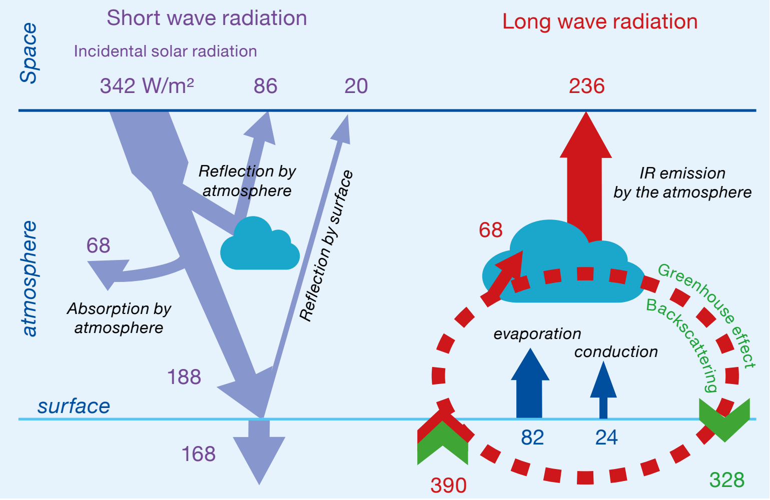

Fig. 1 – **Average energy balance of the whole ocean-earth-atmosphere (in W/m²).** *The Planetary Ocean*, M. Fieux, 2017. ■

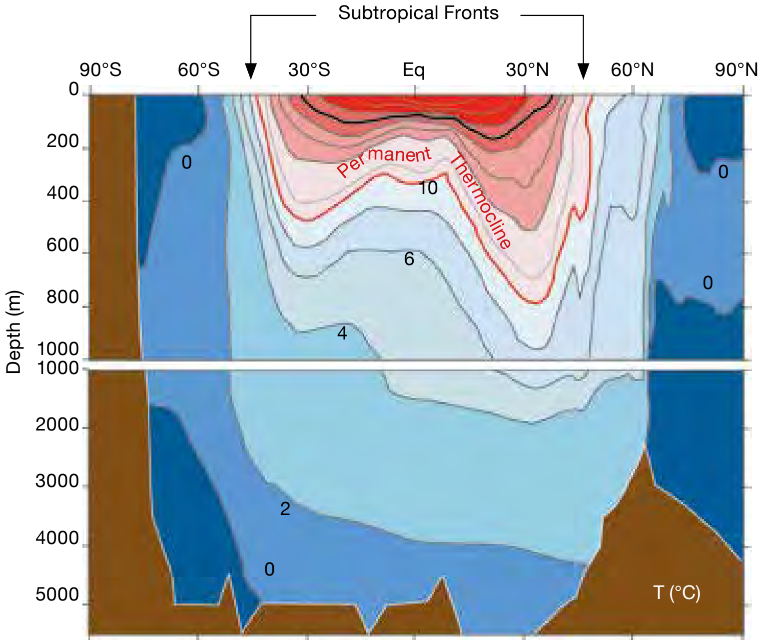

Fig. 2 – **Average temperature along an Atlantic meridional section.** According to LEVITUS, 1982 (*The Planetary Ocean*, M. Fieux, 2017). ■

... in perpetual motion

Water masses are thus formed at the surface under the effect of exchanges with the atmosphere, with unique characteristics of temperature and salinity, which they retain on their long, sometimes millennial journeys. At the surface, they also gain molecules from the atmosphere such as CO_2, CFCs, oxygen... The more extreme the conditions, the denser the mixing and the greater the depth. At high latitudes, extremely cold winds in winter can cause temperatures to drop to the freezing point of sea water, around -1.9°C. By its extraction of fresh water, the formation of ice has the same effect as evaporation. It increases surface salinity and hence density. For example, in the Weddell Sea or in the Greenland Sea, surface-water density is such that convection reaches the bottom. This phenomenon also exists in the Mediterranean, where it occurs around 13°C in the Gulf of Lion and in the Adriatic Sea in areas of high salinity. Some water masses subduct under warmer, lighter water masses in wind-induced convergence zones. This is how the permanent thermocline forms (Fig. 2). These water masses, loaded with oxygen at the surface, thus ventilate the subsurface ocean.

The coldest and densest waters fill the bottom of the oceans. Weddell Sea Bottom Water, being the densest in the open ocean, is the deepest. Its characteristics are mitigated by mixing with overlying water along its path, and channeled by underwater topography. Greenland Sea Deep Water, initially denser than that of the Weddell Sea, as it is more saline, mixes when passing over the sills that separate the Greenland Sea from the North Atlantic Ocean. Together with water formed in the Labrador Sea and water formed in the western Mediterranean, they create North Atlantic Deep Water, less cold but saltier than Weddell Sea Bottom Water, and slightly less dense. This deep water mass spreads southward, to the Antarctic Ocean, the Indian Ocean, and even into the Pacific Ocean. Throughout its course, its characteristics change slowly through mixing with overlying and underlying waters. It is only in regions of divergence that it rises towards the surface, near the Antarctic continent, and by slow diffusion in the Indian Ocean and the Pacific Ocean. There, it is then transformed at the surface through exchanges with the atmosphere, and returns to the North Atlantic where it, once again, undergoes a strong increase in density and then plunges towards the great depths (cf. II.11). The estimated time to complete this circuit can reach up to thousands of years! These movements are due to differences in density between regions, which are the result of the differences in temperature and salinity of the water masses acquired through exchanges with the atmosphere, called 'thermohaline circulation'.

The ocean plays a fundamental role in the establishment of our climate. It stores solar energy, transports it, and transmits it to the atmosphere. It thus helps diminish climate contrasts. Ocean circulation is the main climate-regulating process on the surface of our planet. The ocean provides the short, medium and very long term 'memory' of the atmosphere.

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11. Ocean circulation

Sabrina Speich, Pascale Delecluse, Michèle Fieux
and Gilles Reverdin

The ocean's waters are always moving, at the surface or at depth and their movements are complex. Movement is mainly horizontal, occurring in jet-like flows or eddies, ranging from a hundred kilometres or to a few hundred of metres (Fig. 1). The speed of these movements ranges from a few centimetres/second to more than a meter/second in intense currents such as the Gulf Stream. Vertical movements are much weaker (from a few millimetres to a few centimetres per second) since the ocean vertical scale (i. e., depth) is small (around 5 km) when compared to its horizontal expanse (thousands of kilometres).

The currents are caused by the action of winds, and differences in water density, and are strongly influenced by the Earth rotation and shape of the ocean basins and underwater topography. They are very important for shipping and fishing and play a crucial role in the functioning of the climate system and marine life because they carry accross very long distances (the entire bassin or even more) waters with the properties that characterize them (temperature, salinity and chemical elements such as dissolved oxygen, CO_2, nutrients...). For example, they ensure the transfer of warm tropical waters towards higher latitudes, as happens in the North Atlantic where warm waters carried by the Gulf Stream from the tropics to temperate latitudes (40°N) continues its journey *via* the North Atlantic current to the Arctic ocean (Fig. 1). In this way, the ocean efficiently transfers tropical heat to the subpolar latitudes, thus reducing the thermal disparity between the two regions.

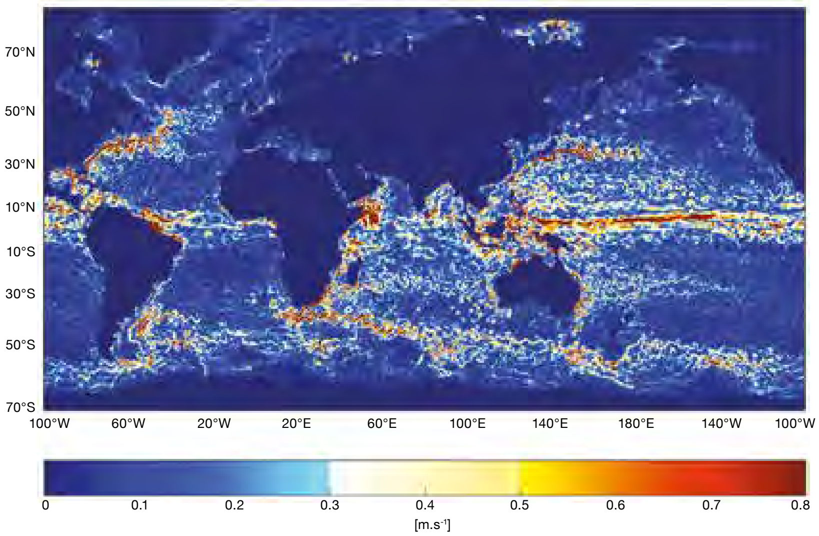

Fig. 1 – **Map showing the intensity of ocean surface currents measured by satellite altimetry.** The speed data used were produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes. ■

The wind and ocean gyres

Dominant winds mechanically pull water into their movement and generate large circular systems known as gyres that extends from the ocean surface down to about 500 meters (Fig. 2). Sub-tropical gyres between the tropics and temperate latitudes carry warm tropical water towards the pole in a western current and colder water towards the equator in an eastern current. Subpolar gyres in high latitudes then take over, carrying water of tropical origin towards the pole in an eastern current and taking polar and subpolar water towards temperate latitudes in a western current. Gyres and average wind direction are linked and, as such, are similar. Subtropical gyres correspond to subtropical high-pressure cells, characterized by Westerly winds between 30° and 40° latitude and by trade winds in tropical regions. In subpolar regions, the first layers of the ocean's surface correspond to the wind cells around subpolar low-pressure areas. The movements of the ocean and the atmosphere are affected by the Earth's rotation. Thus, in the northern hemisphere, water moves clockwise in the subtropical gyres and counter-clockwise in subpolar gyres. The opposite is true in the southern hemisphere.

However, atmospheric high and low-pressure cells and the corresponding winds are much more symmetrical than their oceanic counterparts. The latter are constrained within ocean basins and limited by the effects of the

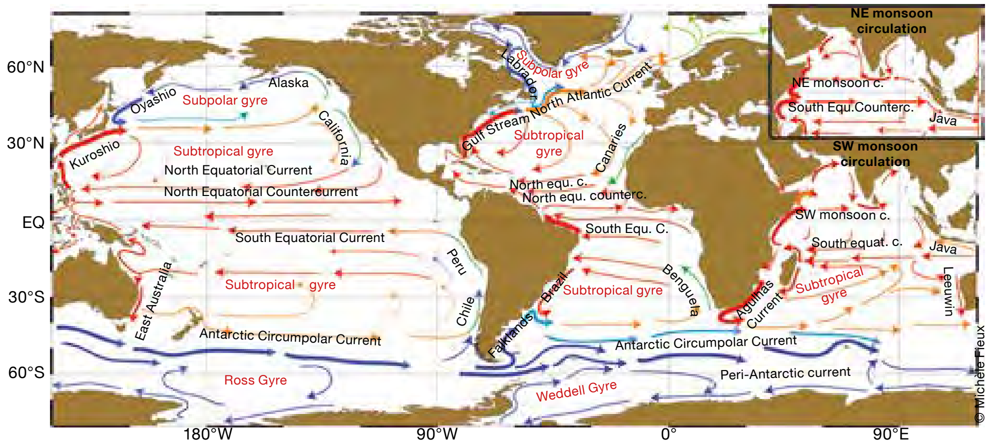

Fig. 2 – **Diagram showing surface current systems.** According to *The Planetary Ocean*, EDP Sciences, 2017. ■

Earth's rotation, thus developing strong east-west asymmetry which causes particularly intense, deep, narrow currents on the western boundaries of the basins, such as the Gulf Stream in the North Atlantic, the Kuroshio in the North Pacific, the Brazil current in the South Atlantic, the Agulhas current in the southern Indian Ocean and the East Australian current in the South Pacific. These currents quickly lose their intensity when they leave the western boundary of the basins. Warm waters, carried towards the poles by these intense western boundary currents, effectively and continuously release heat and water vapor into the atmosphere.

The Earth's climate is influenced by this long, intense transfer of heat and fresh water brought about by the ocean currents associated with the gyres.

Role within the climate system

The ocean currents are guided by the shape of the basins. In the southern hemisphere, there are far fewer large landmasses than in the northern hemisphere, so there is a much larger ocean expanse. In addition, the North Pole region is an ocean covered by sea-ice, whereas the South Pole is a continent, the Antarctic, surrounded by a vast ocean, the Southern Ocean, which stretches as far as the edge of the subtropical region. In the Southern Ocean, winds and currents are not hindered by landmasses and are thus circumpolar. This ocean is thus in perpetual, intense interaction with the atmosphere in extreme conditions (the 'roaring forties' and the 'furious fifties') which give rise to the most intense current in the world, the Antarctic Circumpolar Current, transporting 50 times more water than all the world's major rivers. This current is the link between the different ocean basins and water thus circulates from one basin to another, generating the global ocean circulation.

The global ocean circulation is the interaction of surface water and currents, generated by the mechanical action of wind, with deep ocean currents produced by interchanges between water masses formed in different oceanic regions through local exchanges of heat and fresh water between the ocean and the atmosphere.

This global ocean circulation, illustrated by the concept of 'thermohaline circulation', plays a fundamental role in our climate system because it transfers physical properties, such as temperature and salinity, and biogeochemical properties, such as oxygen, nutrients and CO_2 associated with water masses, over thousands of kilometres. It not only contributes to the redistribution of heat and freshwater to the atmosphere, but also to the chemical balances of the ocean and the planet's major biogeochemical cycles. As such, variations in ocean circulation can trigger considerable meteorological and climatic variations (during El Niño events, for example), or long-term modifications to the climate, such as those linked to significant changes in thermohaline circulation in past climates. They also influence ecological phenomena, such as variations in fish stocks, anoxia events or, on a larger scale, variations in absorption and sequestration of CO_2 by the ocean.

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12. Ocean turbulence: eddies, fronts and filaments

Fanny Chenillat, Pascal Rivière and Philippe Pondaven

For a long time, scientists thought that surface oceanic circulation took the form of large, regular currents over thousands of kilometres, like the Gulf Stream. However, they now know that the ocean is turbulent, particularly thanks to satellite observations since the 1980s (cf. III.4). This turbulence makes oceanic circulation variable at different spatial scales. This study will examine 'mesoscale' turbulence (eddies), several hundred kilometres in scale, and 'sub-mesoscale' turbulence (fronts, filaments and small eddies), on a scale of one to ten kilometres. The dynamics of their structures are highly powerful, fast and unpredictable. They play a dominant role in the transport of the physical, chemical and biological characteristics of the oceans, and potentially in the concentration of micro-waste.

Mesoscale eddies

The mesoscale turbulence of the ocean is characterized by vortices known as 'eddies'. These are dominated by horizontal rotational movements and represent over 80% of the kinetic energy in the oceans. Most of these mesoscale eddies are generated by the instability of oceanic currents. Due to the stratification of the ocean and the Earth's rotation, these currents have an excess of potential energy. This can be released to generate eddies in a few days, and last for several weeks to several months. Seen from above, these near-circular eddies are a few hundred kilometres in diameter (Fig. 1) but they have a depth signature (Fig. 2).

Horizontal speeds within these eddies are on the metre per second scale: faster than those of the average currents. These structures move laterally, often towards the west, at speeds of kilometres per day. As the rotation speed within these eddies is

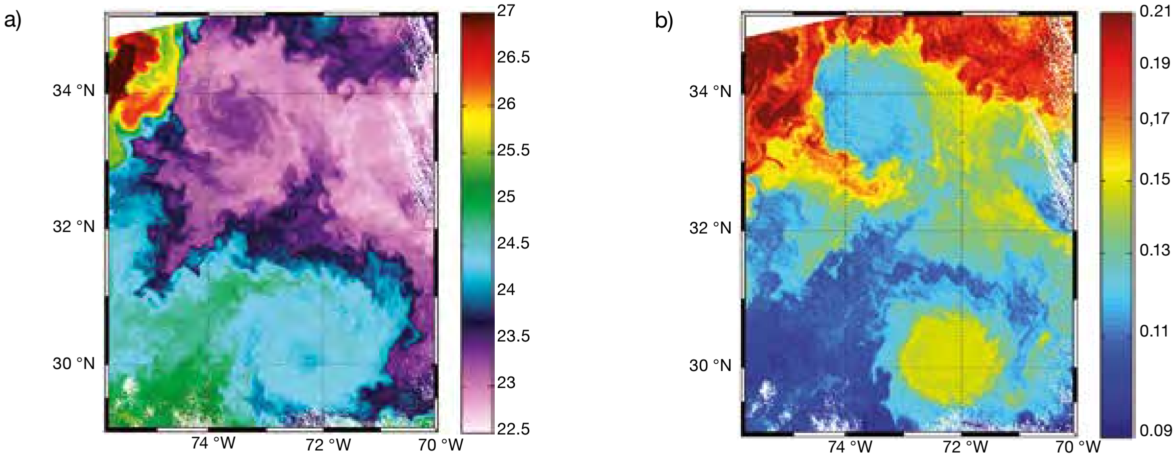

Fig. 1 – **a) Sea surface temperature of the sea in °C, estimated using measurements acquired by the VIIRS radiometer on board the Suomi-NPP satellite. b) Chlorophyll concentration in mg m^{-3} (OCI algorithm, Hu *et al.*, 2012).** We can see the signatures of two mesoscale eddies (warm and high in chlorophyll in the south, and cold and low in chlorophyll in the north), as well as numerous sub-mesoscale filaments and eddies. Source: https://oceancolor.gsfc.nasa.gov, provided by E. AUTRET / Ifremer. ■

higher than the speed at which they move, they can trap water masses, and therefore redistribute them across the ocean basins. Their vertical speeds are generally low: around 1 to 10 metre per day.

Mesoscale eddies are not all identical. Their diameter, rotation speed and movement speed depend on their age and where they formed. Their structure beneath the surface has a depth signature of up to 1000 m, or even several kilometres, thus reaching the ocean floor. However, some have no surface signature. Eddies can rotate either clockwise or counterclockwise: these are known respectively as anticyclonic and cyclonic eddies in the Northern Hemisphere, and vice versa in the Southern Hemisphere.

Sub-mesoscale structures

Between these mesoscale eddies, small structures develop, in the form of fronts and filaments. These structures are short lived, lasting for a few days, which makes them difficult to observe. Seen from above, they are characterized by very strong temperature and/or salinity gradients over several kilometres: these fronts constitute dynamic barriers separating water masses with contrasting properties. Unlike eddies, their vertical signature extends to just a few hundred metres below the surface. The key characteristic of these frontal structures is their intense vertical speeds, which can reach 50 to 100 m per day: much higher than the vertical speeds within eddies. These sub-mesoscale fronts are thought to account for over 50% of vertical oceanic movements in the top 500 m of the ocean. They therefore play a crucial role in the vertical exchanges between the deep oceanic layers and the surface layer. Finally, through instability, these small-scale fronts can in turn generate new eddies described as 'sub-mesoscale' (scale of one to ten kilometres in diameter). The signature of these is confined to the surface.

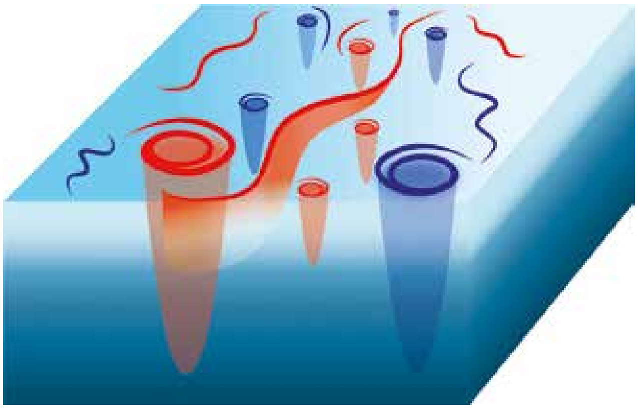

Fig. 2 – **Schematic illustrating the horizontal and vertical structure of mesoscale eddies, and of sub-mesoscale structures (filaments and small eddies).** The surface layer of around 100 m is shown in light blue, and the deep layer in dark blue. © Y. DRÉVILLON / IUEM. ■

Impacts on biology

By their very nature, eddies and fronts impact in various ways on the biology of organisms, ecosystems functions and biogeochemistry. Water masses can become trapped inside eddies, with few or no lateral exchanges with the outside. This makes eddies relatively stable environments for planktonic ecosystems. Nevertheless, exchanges (albeit relatively weak ones) are possible between the deep nutrient rich layers and the sunlit surface layer. Locally, these exchanges can provide the cores of certain eddies with nutrient salts, thus stimulating and maintaining strong primary microalgal production, which is sometimes visible at the surface. The dynamic within fronts and filaments is more intense, and the ascending vertical speeds provide a very effective nutrient supply to the sunlit surface layer, locally stimulating primary production. Because of the intensity of this dynamic, fronts and filaments (and to a lesser extent, eddies) play a key role in the effectiveness of the biological pump and carbon sequestration (cf. II.14). Carbon dissolved at the surface in these structures becomes trapped in the ocean via primary production, and is then exported to the deep layers through sedimentation.

Finally, eddies and fronts are key production zones in the ocean: they are prime habitats for predators (fish, sea lions, sharks...), which aggregate there to feed.

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13. El Niño,
the ‘*enfant terrible*’ of the Pacific

Éric Guilyardi

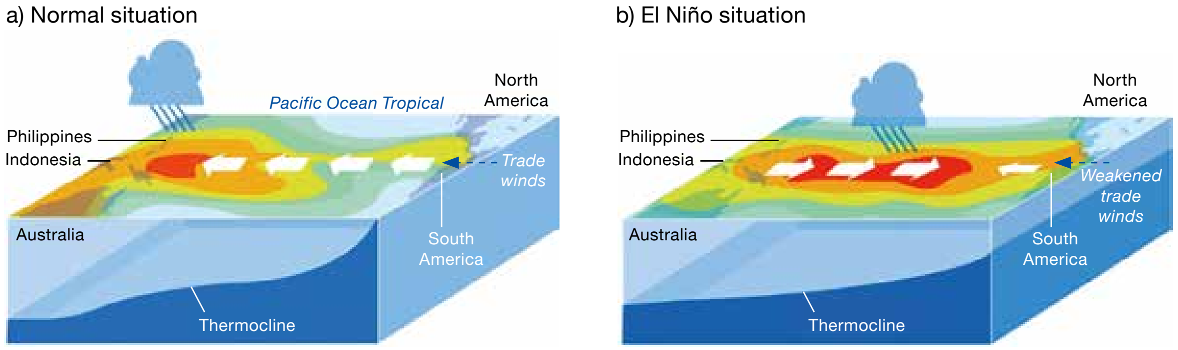
El Niño is the main climate anomaly from one year to the next, It testifies to the magnitude of climate change when linked to ocean-atmosphere exchanges (cf. II.10). These two fluids interact strongly in the tropics and El Niño results from the jolts produced by this interaction. In the tropical Pacific, both the surface ocean and the atmosphere influence each other at the same scales of time and space, unlike the mid-latitudes where they are more independent. In normal years (Fig. a), the trade winds push equatorial warm waters towards the west of the basin. The volume of hot water thus increases, and the thermocline, which separates the cold waters from the warm waters, sinks. To the east, the displaced water is replaced by rising colder water, and the thermocline rises. This temperature gradient between east and west is transmitted to the lower layers of the atmosphere, causing a difference in atmospheric pressure, which strengthens the trade winds, and pushes warm waters westward. In this way, the coupled ocean-atmosphere system is self-sustaining. But every two to seven years, this coupling is disrupted and the El Niño phenomenon occurs (Fig. b). The warm waters of the western Pacific invade the central and eastern equatorial Pacific, reducing the east-west temperature gradient, weakening the trade winds, which can no longer push the warm waters westward, thereby flattening the thermocline.

Environmental impacts

When El Niño starts near the equator in the Pacific, it has global impacts. First, since the tropical Pacific occupies a quarter of the Earth’s surface, El Niño-related warming affects the global temperature by about 0.1°C for each degree of anomaly in the east of the Pacific. Second, it causes major weather changes in many parts of the globe: floods in eastern Pacific countries or in California, droughts in Indonesia or northern Australia, it can change the route of cyclones, with for example, intensification in the Pacific Ocean and a decrease in the Atlantic Ocean. Harvests in many tropical countries are affected, or destroyed. In 2002, India lost 3% of its GDP due to the impact of El Niño on the monsoon. The prices of basic necessities can soar, and fishing in some eastern Pacific countries like Peru may stop abruptly. El Niño has left its imprint on the fishing registers of these countries for several hundred years. The cold waters in the eastern Pacific, which are conducive to plankton activity and hence to fishing, disappear during El Niño and virtually nothing is caught in El Niño years. In northern and eastern Australia, the drought caused by El Niño affects banana and sugar cane plantations and livestock. The effects of La Niña, which, in contrast to El Niño, strengthen the trade winds and increase the east-west temperature gradient of the ocean, can be equally devastating. In particular, in 2010-2011, they caused the worst flooding ever recorded in northern Australia. The environmental impact of El Niño in Europe is low, and its effects are mainly felt through the disruption of global food markets.

Forecasting systems

El Niño events occur irregularly, every two to seven years. They usually begin in the middle of the year and last from six to 18 months, reaching their maximum intensity



a) Normal situation in the tropical Pacific. The trade winds push the warm waters westward. The difference in surface temperature of the sea (in color) between east and west creates a difference in pressure and maintains the trade winds. **b) An El Niño situation.** The trade winds weaken and warm waters invade the center and the east of the tropical Pacific, modifying the wind and rainfall regimes all over the planet. ■

towards Christmas (hence their name). These major phenomena have led to the establishment of seasonal prediction systems to anticipate the arrival of El Niño or La Niña. Although these systems are reasonably reliable from the boreal summer preceding the winter maximum of these events, their predictability in the spring is almost impossible making preparing for them arbitrary for a period of more than six months.

El Niño has traditionally been studied more particularly by oceanographers, but research in recent years, particularly in France, shows that the atmosphere could be responsible for both triggering the events and for their diversity. Spring 2014 being a good example: a very strong heat anomaly in the ocean, a 'classic' precursor of El Niño, suggested that a major event was developing. The absence of a reaction by the atmosphere took all the experts by surprise and the event came to a premature end. However, in 2015, a major event occurred and many studies reported the primary role of a succession of western wind anomalies over a period of 5 to 10 days that shifted the event from the 'normal' to the 'extreme' category.

Impacts of global warming

El Niño has existed for several million years and its precise observation – especially deep in the ocean – has been possible for about 30 years. A question on everyone's lips is of course: Can El Niño and its impacts be altered by climate change? The first consequence of climate change is the intensity of this extreme phenomena. A warmer atmosphere contains more moisture, and so, when it rains, it rains harder. And when it rains a lot, like during a cyclone, it rains a lot harder. What about the average properties of El Niño itself? While its average intensity, frequency and position appear to remain unchanged, studies suggest that under the pessimistic scenario, the frequency of extreme events could double. Today, an extreme El Niño, like those in 1997-98 and 2015-16, takes place one time out of six (about 4 to 5 times per century). If we continue to do nothing to limit the ongoing climate change, this frequency will increase to one event out of three (10 per century). Yet another incentive, if one were needed, to drastically reduce our emissions of greenhouse gases.

The impact of climate change in the tropics is feared, as it affects half of the world's inhabitants, and who are often the most vulnerable. This impact can be multiplied by El Niño, which adds its effects to those of current deregulation. Anticipating the regional disturbances ahead therefore requires a better understanding of the major El Niño phenomenon and its possible changes. This is one of the research priorities in climate science.

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14. The ocean: a carbon sink

Laurent Mémery

Over timescales ranging from the seasonal to several thousand years, the ocean plays a major role in governing carbon dioxide levels in the atmosphere. This role is a result of the characteristics of CO_2: a gas which is chemically active in the ocean and which plays a fundamental part in marine biological activity.

The solubility pump and the buffer effect

CO_2 is exchanged between the atmosphere and the ocean by gas transfer processes: it penetrates *via* dissolution and escapes *via* degassing. These exchanges are more intense when wind speeds (and therefore surface turbulence) are high. Moreover, the solubility of any dissolved gas decreases when the temperature rises. Large-scale circulation is characterized by the transport of warm surface waters towards the poles. Due to cooling and increased density, these waters then tend to sink into the deep seas (cf. II.11). During this transport, the temperature decreases, but the solubility (and therefore the ocean's capacity to absorb CO_2) increases: carbon-rich waters are transferred to the deep ocean (2000 m and deeper), thus isolating dissolved CO_2 from the atmosphere for several hundred years. This process is called 'the solubility pump' (Fig. 1).

Furthermore, dissolved CO_2 is a weak acid: when exposed to water, it is almost entirely transformed into carbonate ions (CO_3^{2-}) and bicarbonate ions (HCO^{3-}). This is why the dissolved inorganic carbon (DIC) content of the ocean is extremely high. Consequently, a 1% variation in the DIC content leads to a variation of around 10% in the partial CO_2 pressure. This figure increases with temperature and the DIC load (the Revelle factor).

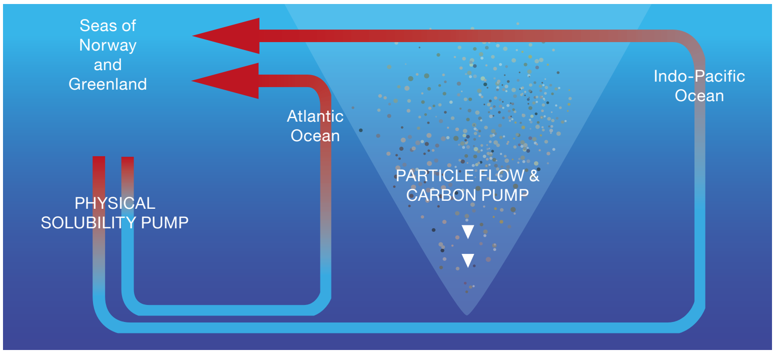

Fig. 1 – **The arrows indicate large-scale thermohaline circulation, showing the descent of CO_2 rich cold waters in the polar seas, their displacement at the bottom of the ocean and their return to the surface to complete the circuit: this is the solubility pump.** Primary production at the surface generates particle matter which sediments in the deep ocean due to gravity, while also being largely biodegraded in the water column: this is the biological pump. These two processes are responsible for CO_2 storage in the deep ocean. ■

The biological pump

Marine microalgae are produced by photosynthesis, which requires nutrients and light energy. It therefore occurs at the surface of the ocean, in the euphotic layer. Certain elements present in trace amounts, such as dissolved iron, are also limiting nutritional elements. Thus, in oceanic regions which are distant from the continents, such as the Southern Ocean, photosynthesis is not limited by the nutrients nitrogen (N) and phosphorus (P), but by these micronutrients. Moreover, certain algae produce a kind of shell (Fig. 2), like those of diatoms (silica) or those of coccolithophores (calcium carbonate). These microalgae then supply trophic networks, with a significant loss (around 80% for each trophic transfer) through respiration and oxidation. Ultimately, around 10% of primary production ends up as detritus: particles which sediment (export) towards the interior of the ocean. This process is called 'the biological pump'.

The transformation of inorganic matter (DIC, and nutrients) into organic matter (algae) through photosynthesis consumes CO_2 and produces oxygen at the surface. Respiration and other metabolic processes, such as bacterial activity, are responsible for the reverse transformations in the deep ocean: overall, DIC and nutrient contents increase with depth, whereas the oxygen content decreases. On balance, although 5 to 10% of organic carbon produced at the surface is exported to the deep ocean through particle sedimentation, less than 0.1% reaches the sediments (a low relative value, but the process is fundamental on the geological scale). The rest is remineralized in the water column. A rough calculation shows that the 10% decrease in DIC at the surface due to photosynthesis produces a 100% variation in dissolved CO_2 (a Revelle factor of around 10). An abiotic ocean (without photosynthesis) would therefore double the dissolved CO_2 content. Consequently, the atmospheric content, in balance with the ocean, would be double the observed natural content (before anthropic disturbances). The impact of the biological pump is thus amplified by the chemistry of CO_2.

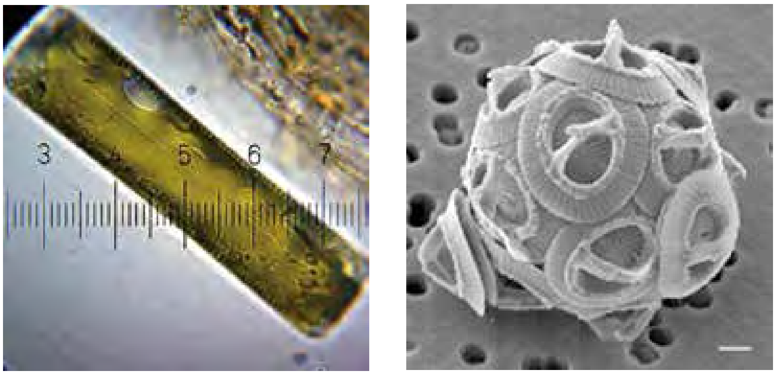

Fig. 2 – **Left: diatom with its silica frustule.** Right: Coccolithophore with its calcium carbonate coccoliths. ■

The ocean and the absorption of anthropic CO_2

The physical and biological processes, amplified by the specific chemistry of carbonates, thus explain why the ocean greatly restricts the natural atmospheric CO_2 content. But what about anthropic CO_2 and its absorption in the context of climate change? Currently, the ocean absorbs around 30% of the CO_2 injected into the atmosphere by human activity.

The temperature of the ocean is rising, particularly at the surface, and this increase will only grow worse in the course of the 21st century. This change tends to decrease solubility, and with it the Revelle factor: the exchange of CO_2 from the atmosphere to the ocean will therefore become less effective, leading to positive retro-action. The more the atmospheric concentration of CO_2 increases, the less capable the ocean is of absorbing anthropic CO_2; and the more CO_2 remains stored in the atmosphere, the more the atmospheric temperature rises. On the other hand, relatively simple heat balancing considerations and the results of numerical modelling indicate that climate change is associated with a modification of oceanic circulation, in particular the intensity of the formation of the cold waters that descend to the depths in the polar regions. This large-scale thermohaline circulation is thought to be slowing down (cf. I.3). As a result, the physical transport of CO_2 from the surface to the deep ocean should decrease in the short and medium term, also constituting a positive retro-action.

The potential role of the biological pump is highly uncertain, and should only be felt over longer timescales. At a first analysis, the intensity of the biological pump is connected with the intensity of the vertical input of deep ocean nutrients. Since warmer waters are less dense, the temperature increase at the surface should intensify stratification, which will cause a decrease in the vertical input of nutrients. However, these vertical carbon inputs should also decrease, and this process could initially compensate for the diminished biological pump. Therefore, from a first approximation, it appears that the balance would remain neutral. Other than in regions limited by external inputs, such as wind inputs (iron in the Southern Ocean), only physiological and ecological processes can alter the effectiveness of the biological pump. Understanding these processes is a major challenge for current research.

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15. Sea level

Anny Cazenave

The oceans are routinely monitored by numerous satellites (cf. III.4), which measure the temperature and salinity of the sea's surface, the currents, the waves, the biological activity of the surface waters, and the sea level rise. This last factor is one of the best indicators of climate change today. Greenhouse gas emissions from human activities not only cause the average temperature of the Earth to increase, but also that of the ocean, making it dilate. In turn, warming and its effects are responsible for glaciers melting and for the polar ice caps losing mass. The warming of the ocean and the melting of continental ice sheets are the main contributors to rising sea levels today.

Advances in altimetry

The tide gauges installed along certain continental coasts and on some islands provide us with valuable historical information on the sea level rise before the space age. However, the further back we look, the sparser the data, and it remains very difficult to precisely estimate the sea level rise over the 20th century. The most recent results give an average rise speed of 1.1 to 1.9 mm per year (Fig. 1).

Since the early 1990s, high-precision altimetry (the Franco-American missions Topex/Poseidon and Jason-1, 2 & 3, the Franc-Indian mission SARAL/Altika, and the ERS missions Envisat and Sentinel 3 by the European Space Agency) has been used to continuously track variations in the sea level, with remarkable precision and near global coverage. Although the concept of altimetric sea level measurement is simple, many factors require correction to achieve the desired precision. These include instrumental drift, distortions between successive missions and due to physical phenomena such as delays in the propagation of the radar wave through the atmosphere, interaction between the state of the sea and the electromagnetic wave, and the tides. We also need to know the satellite's trajectory very precisely, and until recent years, orbit errors were the greatest source of uncertainty in altimetric sea level measurements. The constant reduction of all these error sources affecting altimetry systems, the intercalibration of missions that are in orbit simultaneously and the recent reprocessing of data from past missions now allow us to provide a long and extraordinarily precise time series for average global sea level and its regional variations.

Rising sea levels

Since 1993, the sea level has risen by 8 cm on average. Recent studies have shown the non-linearity of this increase: the rise has accelerated in the last ten years, with an increase of

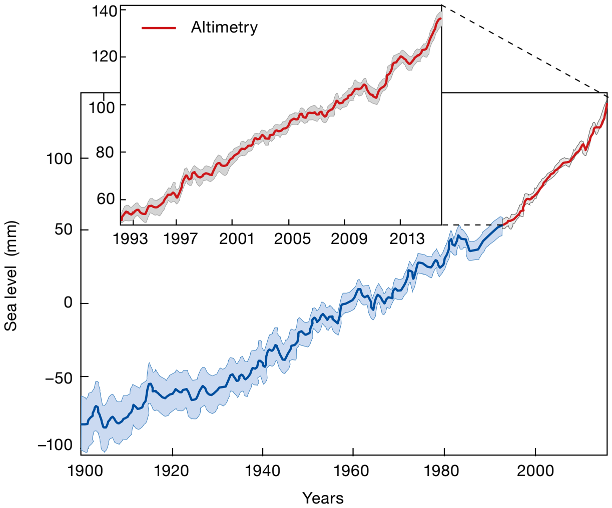

Fig. 1 – Sea level rise since 1900. The blue curve shows the rise in the average level according to tide gauge measurements. The red curve and the inset show the global average sea level measured by spatial altimetry since 1993. According to Church and White, 2011. ■

around 30% compared to the preceding decade. This is because of accelerated melting of the Greenland ice sheet. Today, oceanographers have different spatial and on-site observation systems to estimate the different contributions to rising sea levels. Using data from the ARGO project (cf. III.3), scientists can calculate the thermal expansion of the upper 2000 m of the ocean, with almost global coverage. Spatial gravimetry (the GRACE mission launched in 2002, which measures how mass redistributions on continents and in the ocean affect the Earth's gravity) not only gives us a direct measurement of variations in the ocean's mass (and therefore of the contributions of freshwater inputs to the sea level), but also of the melting of glaciers and the decreasing mass of the Greenland and Antarctic ice sheets. Comparison of the rising sea levels observed by altimetry and the sum of the contributions reveals strong correspondence, showing that the different observation systems are robust. It is also a valuable tool for validating the climate models used to simulate the future climate, including rising sea levels.

Thanks to their complete coverage of the oceanic domain, altimetry satellites have revealed that the rise in sea levels is far from uniform (Fig. 2). In the western Pacific, for example, the sea has risen three times faster than the average over the last 25 years. This significant regional variability is governed by the uneven warming of the ocean. As a result, the sea has risen more in regions of the ocean that have stored more heat. This is the case of the tropical western Pacific: since the start of the 1990s, the trade winds have intensified, and have driven the warm surface waters towards the west of the basin. With the deepening of the thermocline in this region, the thick layer of warm water has caused the sea level to rise more than it has elsewhere.

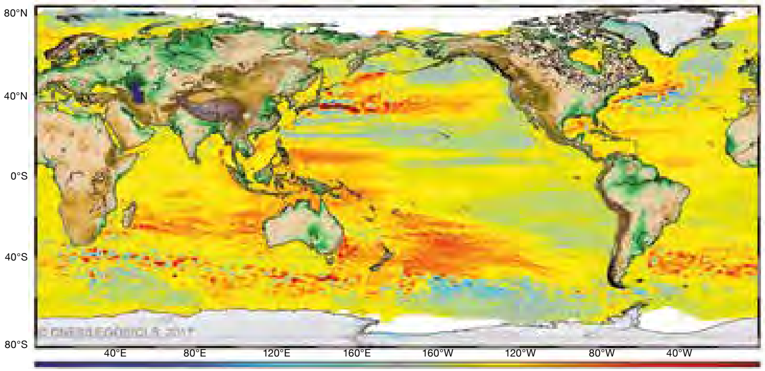

Fig. 2 – **Regional sea level trends observed by spatial altimetry, from 1993 to 2016 (in mm/year).** Source: AVISO. ■

Monitoring rising sea levels

Rising sea levels are a worrying threat for many of the planet's low-lying coastal regions, which are often heavily populated. In addition to the rise in connection with climate change and its significant regional variability, other non-climatic phenomena amplify the effects of the climate. These include the sinking of the bed level, due to sediment accumulation in the deltas of large rivers, or to groundwater pumping and oil or gas extraction. Recently, a number of researchers have taken a particular interest in coastal phenomena and the potential interactions between large- and medium-scale sea level rise (as measured offshore by altimetry) and small-scale oceanic processes affecting the coastal zones (coastal currents, waves and fresh water inputs in estuaries). The latter processes can modify the coastal sea level rise. Whereas traditional altimetry does not provide good measurements between the coast and 10 km offshore (because the landmasses cause parasite reflections of the radar wave), new technologies such as the SAR altimetry of the European Cryosat and Sentinel 3 missions, and soon interferometric altimetry by the Franco-American SWOT mission, will allow us to precisely measure the sea level along the coasts on a very fine scale. Their results are keenly awaited.

Continuous, long-term and global measurement of the changes in the sea level using spatial altimetry, offshore and by the coast, is a crucial objective for ocean monitoring. As well as being useful for detecting a possible acceleration of the sea level rise, these observations are also essential for the validation of the climate models used to simulate future rising sea levels, and to study their impacts in the planet's heavily populous, low-lying coastal regions.

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16. Dynamics
at the land-sea interface

Patrick Marchesiello and Rafael Almar

The coastal zone is the interface between land and sea and is the site of some major societal challenges, with growing anthropogenic pressure (demography and use of resources) in a dynamic zone subject to significant natural hazards, principally erosion (Fig. 1) and submersion. These risks may intensify with rising sea levels or under the influence of more intense weather events. However, it is difficult to predict the evolution of the hydro-morphodynamic system that functions in a non-linear manner and where there are still many uncertainties. It is therefore vital that we improve our knowledge of the processes at work, and enhance the observation and modelling tools available, so that we can put forward integrated coastal management strategies.

From the deep ocean to the inner continental shelf

The continental margin needs can be scaled down to study the numerous circulation regimes and as many transitions from the ocean up to the shore. Contrary to the deep ocean, where the energy spectrum is largely controlled by the turbulent cascade, coastal dynamics are influenced by multiple types of forcing (wind, tide and waves) and constrained by bathymetry (cf. III.2). The continental slope is the outer boundary of this coastal interface. It is the source of strong vertical movements and generates internal tides that may reach the coast, as well as slope currents that form an effective barrier to land-sea exchanges.

This is especially true on the western boundaries of the oceans where Rossby waves accumulate and, through rectification, form major currents such as the Gulf Stream. On the other hand, on the eastern boundaries, persistent winds drive water masses away from the coast and prompt the upsurge of deep water, forming strong, turbulent streams, where shelf and ocean waters mix.

These upswellings have a major influence on the weather (*e.g.* sea breezes) and on coastal ecosystems. However, nearer the coast (from around 30 m deep), their dynamics are modified in a more frictional zone where the surface and deeper layers meet: the inner continental shelf.

From the inner continental shelf to the shore

On the inner continental shelf, winds tend to drive water masses in their direction (contrary to in deeper waters). In places, river plumes create marked stratification and dynamically active fronts (Fig. 2). The tide also generates intense currents, through resonance and through the concentration of energy in bays (funnel effect) and in

Fig. 1 – **The city of Hoi-An in central Vietnam is included on the UNESCO World Heritage List.** It used to be a prosperous city, thriving on maritime trade but its activity declined as its river silted up. Today, its beaches are subject to extreme erosion, requiring emergency but sustainable measures and therefore close understanding of the processes at work and predictive models. © R. ALMAR. ■

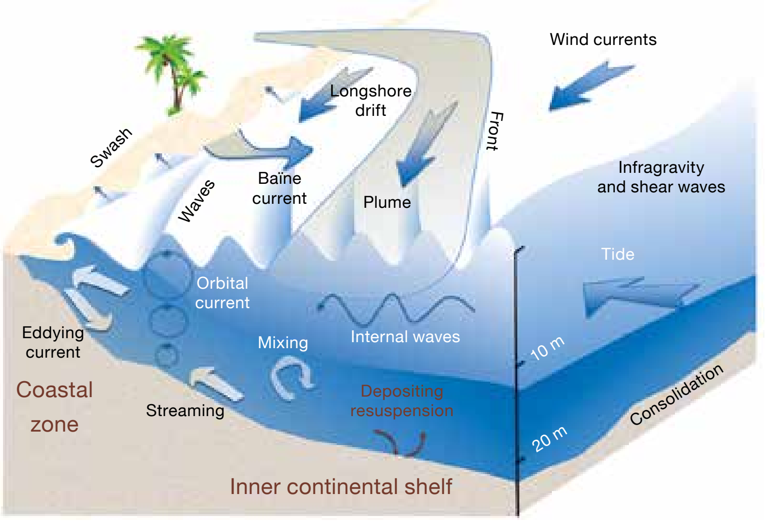

Fig. 2 – **Diagram showing circulation on the inner continental shelf and the coastal zone.** ■

shallows, slowing down the wave (as in the Bay of Mont Saint-Michel).

These currents have a residual component and, therefore, an effect on sediment transport and morphological evolution. At the same time, waves start to interact with the sea bottom (at depths of less than a quarter of their wave length). The speed of waves falls and their energy is concentrated in shorter but higher waves. Parallel to this, bottom friction has a dissipative effect and orbital speeds stir loose seabed material and move sediments.

Coastal hydrodynamics

Waves are the main component driving coastal dynamics. They disseminate the energy transferred by the wind at the ocean's surface from the offshore area towards the coast, often over several thousand kilometres. As they approach the coast, part of the waves' energy is dissipated by the swell. This energy is transferred to mean ocean circulation with currents that can exceed 1 m/sec (longshore drift, baine currents, eddying current), to waves with lower frequencies, known as infragravity waves (0.5 – 5 min), or to shear waves and instabilities (5 – 30 min). Setup, *i.e.* the increase in the mean water level due to the presence of wave swell (around 20% of wave height at peak swell), works in conjunction with the tide and wind to produce surges with a mean exceedance (over the wave period) of the high-tide water level. However, the maximum sea level is attained through transitory movements in the swash zone, which is the final interface with land, integrating every transformation of the wave from the time it was generated. Infragravity waves are especially active during storms, increasing submersion risks.

Land-sea exchanges

Because currents on the coast and at sea have distinct scales and dynamics, they are usually measured and modelled separately, implicitly suggesting that there is little interaction between them. The study of continental shelf and offshore interchanges has developed widely over the last 15 years, but this is not the case for continental shelf/shore interchanges. Yet recent work has proven that bringing these historically distinct areas of study together can be very useful. For example, the stratification and vertical shear of currents are often neglected in studies of the shore area, as is the Coriolis Force. Nonetheless, three-dimensional processes appear to enable offshore propagation of eddies and facilitate exchanges between the shore and the continental shelf.

Hydro-morphodynamics

Finally, we cannot consider the coastal zone without referring to morphological changes, especially on sandy coasts (which account for 70% of coastlines in the world). The shoreline constantly adapts to very variable oceanic forcing and a balance is rarely, if ever, achieved. In turn, coastal morphology affects hydrodynamics. For example, the impact of a storm will be different if it comes on the back of another one, with natural self-protection mechanisms such as the formation of offshore sand bars, which dissipate wave energy. The shore areas are naturally resilient to oceanic climate change (waves and sea level), a quality that is considerably threatened by human developments (cf. V.15).

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17. The oceanic biosphere

Gilles Boeuf

To truly grasp the scale of the ocean, it is necessary to consider its volume, which totals 1370 million km^3. Its average depth is around 3800 m, and the main characteristic of this gigantic environment is its continuity, and therefore its connectivity. It also differs from other bodies of open water on the planet in its salinity. This is stable offshore (35 g of salt per litre, 1050 mOsm.l^{-1}), although salinity differences do of course play a fundamental role in oceanic circulation. Finally its third characteristic is its stability: the composition of oceanic water is the same everywhere, and has been for tens of millions of years (Fig. 1).

Biodiversity cannot be reduced to a simple list of species populating a given ecosystem: it is much more than just a catalogue or an inventory. Rather, it corresponds to all the relationships between living beings and their environment: it is the living part of nature. Biodiversity is the product of a prebiotic chemistry, built on preceding geodiversity, and it diversified in the ancestral ocean around 3900 My (million years) ago. Around 3400–3200 My, cyanobacteria began to conquer the ocean, which at the time contained no atmospheric oxygen.

Marine biodiversity

The known species diversity in the ocean accounts for no more than 13% of all living species described to date, or less than 260,000 of the 2 million identified species on Earth. This is primarily due to our lack of knowledge (especially about the deep-sea zones and about microorganisms, bacteria and various protists), which leads us to considerably underestimate oceanic biodiversity (cf. III.17). For all the prokaryotes (bacteria) and the very small eucaryotes (protists, yeasts, microalgae and microfungi), molecular approaches are yielding astonishing knowledge every day. Very recently, the *Tara* Oceans expedition around the world's oceans provided precise information (cf. III.6) on the abundance and variety of viruses, bacteria and protists (over 500,000 new species potentially discovered). Moreover, it is clear that marine ecosystems and the living behaviours of the species that populate them (dispersion of sex cells and of larval stages in a continuous environment), create a lower predisposition to strict endemism than in terrestrial biotopes . There are far more barriers and isolates favouring speciation (the evolutionary process by which new living species appear) on land (including in fresh water) than in the sea. This leads to major differences in species diversity: marine ecological niches offshore are not as rich as terrestrial niches, which are more fragmented and favour new speciations. There are far fewer known species in the sea, but the various ancestral groups are more numerous than on the continents. Today, for example, 12 animal *phyla* are exclusively marine and have never left the ocean. These include echinoderms, brachiopods and chaetognaths.

The physical consequences of the osmotic 'flows' (water and electrolytes, 'salts') in this salt water environment have produced two types of strategies for osmoregulation (regulation of water and salts) among living organisms.

Fig. 1 – The Great South Reef, New Caledonia, 2009. © G. BOEUF. ■

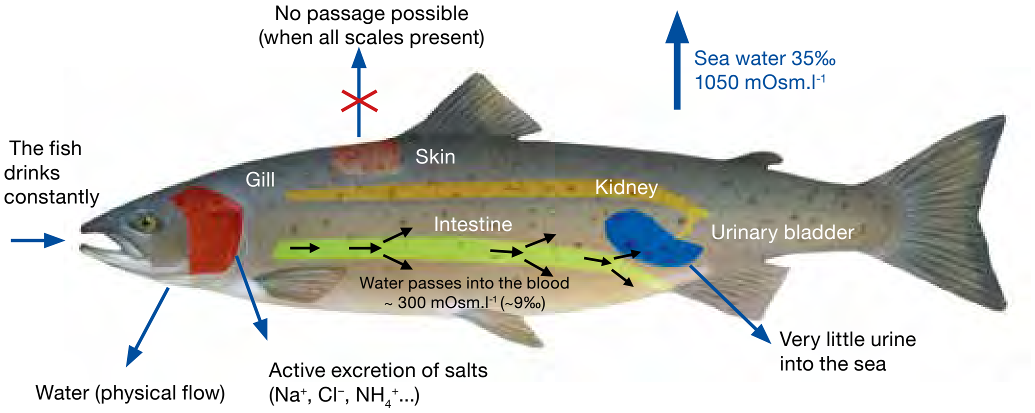

Fig. 2 – **Osmoregulation of a bony fish in the sea.** According to G. BOEUF, 1987. ■

Living with salt

The ocean has contained sodium chloride for a very long time, and scientists can now explain this stable salinity. The billions of tonnes of cations (calcium, potassium, magnesium, sodium...) brought by rivers for as long as they have flowed are balanced out by trapping in marine sediments and the formation of limestone (for calcium), and by clay adsorption (for potassium). Magnesium and sodium are retained at the mid-ocean ridges (serpentinization and alteration to clay of pyroxenes and olivines). For anions, bicarbonates are in permanent exchange with the atmosphere and biosphere, and chlorine, which is not part of any large biogeochemical cycle, is thought to have been dissolved in sea water from the outset (it was among the original volatile elements) and to have remained there. Therefore, marine life has always had to deal with salinity, and has developed a universal 'intracellular isosmotic regulation' strategy. Consequently, the vast majority of invertebrates and certain vertebrates have the same osmotic pressure (internal environment and cells) as that of seawater. Another strategy, which appeared with certain crustaceans around 700 million years ago and is known as 'extracellular anisosmotic regulation', gives species great capacities for migrating and moving between environments, whilst keeping the osmotic pressure of their cells and bodily fluids within a narrow range (between 300 and 400 mOsm.l^{-1}, compared to 302 in humans), whatever the external salinity. Marine osmoregulators (like bony fishes) have thus been forced to develop strategies of permanently drinking seawater and excreting salts through the gills, since the kidneys alone cannot complete this task (Fig. 2). One of the main problems posed by terrestrial life is keeping water within the organism and avoiding dehydration.

Coastal systems, which are intermediary with strong terrigenous influences, are subject to much larger variations, and the 'strategies' seen there are much closer to those used on land. The marine environment has therefore played a decisive role in the history of life, and the current ocean still retains its primordial role in the evolution of life and the climate. Should humans, who so greatly disturb and degrade the oceanic environment, not remember that they too are 'salty'. We have a very stable internal environment (140 millimoles of sodium and 105 mM of chloride in human blood), with an osmotic pressure between that of seawater and that of freshwater. This should remind us that hundreds of millions of years ago, we came out of the ocean. By remembering this, we should feel much more integrated in the 'Earth system' and rediscover greater harmony with our ocean.

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18. Marine food webs

Philippe Gros

Some 550 million years ago (My), an evolutionary burst filled the seas with an astonishing diversity of animals – a revolution which triggered the emergence of complex food webs. At the core of these networks are the primary producers: by synthesizing organic matter (OM), they provide food to various types of consumers such as predators, their prey and detritivorous organisms. The dynamics of these trophic interactions – who eats whom – are a basic feature of biodiversity.

The sources of energy

From the time the Earth formed, around 4.6 billion years ago (Gy), the earliest life forms emerged within the first billion years period: mats of chemoautotrophic bacteria did produce OM by harnessing the chemical energy of molecules (such as hydrogen) generated by water-rock reactions. Evidence suggests that functional diversity did already exist: heterotrophic bacteria fed on waste products of chemoautotrophic bacteria, while viruses transported genes throughout their bacterial hosts.

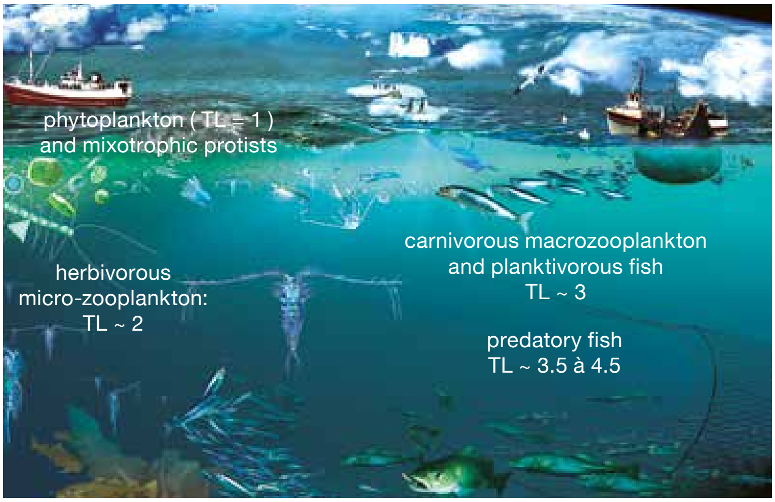
Around 2.7 Gy – at this time, the Earth's atmosphere was lacking oxygen – cyanobacteria went on to develop a major innovation: the oxygenic photosynthesis. This process harnesses the energy in sunlight to synthetize organic compounds and incidentally enriches the atmosphere in oxygen (O_2). As a result, by 2.3 Gy, the atmospheric O_2 levels had risen to 0.1–1% of the present level (21%). By 1.8 and 1.2 Gy respectively, two momentous events took place: the emergence of the eukaryotic cell (unlike bacteria, genetic material is enclosed within a membrane-bound nucleus) and the emergence of the red algae. Wide oxygenation of the ocean would not happen until less than 1 Gy.

The common ancestor of all living animals – likely a multicellular bacterivorous marine eukaryote – arose nearly 800 My. Progress in understanding the evolution of complex multicellularity, a striking feature of animals, requires a theory combining environmental changes, selective pressures and biological innovations.

Today, anaerobic bacteria thrive in the absence of O_2 and sessile sponges survive at very low O_2 levels. In contrast, O_2 provides enough energy to power the active lifestyle of large-sized mobile animals, allowing for prey hunting and predator avoidance behaviours. By 550 My, the widespread acquisition of energy through flesh-eating – animals eat other life forms, especially other animals – triggered the outbreak of complex food webs with many types of eaters.

The primary producers

Drifting in the sunlit oceans' surface waters, single-celled photosynthetic organisms – the phytoplankton – are the foundation of the ocean food web, providing OM to virtually all marine heterotrophs. Phytoplankton comprise single-celled algae (such as diatoms) and photosynthetic cyanobacteria, the latter further able to fix atmos-



A schematic overview of a North Atlantic food web. © G. GORICK. ■

pheric nitrogen they can use to make proteins.

Since the 1990s, approaches bringing together taxonomy, ecology and large-scale genomics have revealed the tremendous diversity of the microplanktonic community. This living interface between atmosphere and the ocean's interior is teeming with viruses, bacteria and protists – a broad group of single-celled eukaryotes.

Protists comprise autotrophs (microalgae: diatoms, coccolithophores...), small heterotrophs (nano- or microzooplankton) and mixotrophs (combining auto- and heterotrophy in the same cell). Among numerous variations in mixotrophy, some photosynthetic species ingest organic particles – 'phytoplankton that eat' – while some heterotrophs hold microalgae.

Most protists at the base of the plankton food web are not strictly producers or consumers. Before being available to larger animals, the photosynthetic production of microalgae and cyanobacteria spreads through a complex network of small mixotrophs and heterotrophs. The quantification of ecological effects of mixotrophy is still in its infancy.

Phytoplankton provide us with vital ecosystem services: they emit half the O_2 permeating our atmosphere; they drive a 'biological pump' moving carbon (dead diatoms...) from the atmosphere to the deep ocean for hundreds of years, bringing down the atmospheric level of CO_2 and helping to control Earth's climate; they fuel almost all marine life, inter alia the hundred million tonnes of fish, molluscs and crustaceans landed every year by world fisheries.

Emergence of a super-predator

The trophic level (TL) of an organism is an indicator of its ecological role. The TL is defined as 1 for phytoplankton. This level corresponds to the 'net primary production' (NPP): the amount of CO_2 fixed by photosynthesis, less the quantity of CO_2 released by the respiration of phytoplankton. NPP is the photosynthetic production actually available in the food web.

The TL of heterotrophs is calculated as follows: TL = 1 + the average of the TLs of the prey species in the diet. Copepods—planktonic crustaceans of about 1 mm in size—are examples of first-level heterotrophs. Herbivorous copepods (TL = 2) feed directly on NPP by filtering seawater to catch microalgae. They in turn are prey for carnivorous copepods and 'gelatinous plankton' (TL = 3). Planktivorous fish (herring, sardine, anchovies...) consume a mix of phytoplankton, herbivorous and carnivorous zooplankton and detritus; their TL is thus about 3. The TLs of predatory fish, else pelagic (tuna, marlin...) or living close to the seabed (cod, anglerfish...) rise to 3.5–4.5.

The above TL values are for adult fish (the TL changes with age, as it generally depends on the ratio of the size of the fish's mouth to the size of its prey). The Atlantic cod, a major predator, starts life as a planktonic larva hunted by herring, which are in turn prey for adult cod – a feedback partially explaining the unexpected failure of the 1992 fishing ban on Canadian cod. Overexploited in the 1960s–1970s, cod collapsed in the 1980s and did not recover thereafter, resulting in a marked increase of herring abundance. Once depleted, adult cod populations were unable to withstand the strong predation of abundant herring on cod larvae ...

With the burning of fossil fuels by the end of the 19th century, humanity became a super-predator who disrupted the functioning of food webs. Motorised vessels could indeed exploit the marine ecosystems further away, for a longer time and at greater depths. This is evidenced by the current poor state of many fisheries: after six decades of increase in engine power, the global efficiency of the world fishing fleet (in terms of tonnes of catch per fishing effort) is now less than in 1950, despite its spreading throughout the whole ocean.

The crucial challenge consists in keeping ocean productive and in good health, while consolidating the preservation of marine biodiversity and the sustainability of its exploitation. Within this context, regulating the human ecological footprint is the cornerstone of a viable use of marine food webs.

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19. The deep oceans: interfaces with the lithosphere

Catherine Mével

The deep oceans only began to reveal their mysteries in the middle of the last century, when technological advances allowed us to map and explore them. It was then that scientists discovered that the outer layer of the Earth is composed of a mosaic of rigid lithosphere plates, moving relative to each other. Plate tectonics reflects the dynamics of convection currents in the Earth's mantle, driven by the planet's internal heat. Plates are created at mid-ocean ridges, where the mantle rises and magma is produced, forming the new oceanic crust. They move laterally before disappearing, descending down into the mantle at subduction zones (Fig. 1). Denser than the continents, the oceanic plates lie deeper and are therefore covered by the oceans, which mask almost 70% of the Earth's surface. It is the dynamics of these plates that shape the deep ocean floor.

Mid-ocean ridges

Mid-ocean ridges form a huge underwater mountain range, running for over 60,000 km along the ocean floor. This huge volcanic protrusion, where activity is almost permanent, rises nearly 2000 m above the surrounding abyssal plains, and peaks at a depth of around 2000 m. The newly created oceanic lithosphere is moving symmetrically to the axis of the ridge, at speeds of a few centimetres per year. This plate divergence creates an axial valley, bordered by a system of faults. Its depth varies from a few hundred metres for the fastest ridges to several kilometres for the slowest ones. At the ridges, the ocean floor is therefore composed of large, volcanic outpourings, some more fractured than others. They form flows of pillow lavas, due to the sudden cooling of the lava on contact with the seawater (Fig. 2). Beyond the axial valley, the relief is composed of abyssal hills, parallel to the direction of the axis, which become progressively buried under the sediments. Seawater has infiltrated the new oceanic crust ever since its creation. The heat from the rising magma causes the installation of hydrothermal convection cells, which are responsible for the formation of black smokers. The smokers expel very hot fluids (~ 350 °C) loaded with sulphur and heavy metals, and cause metal sulphide deposits on the

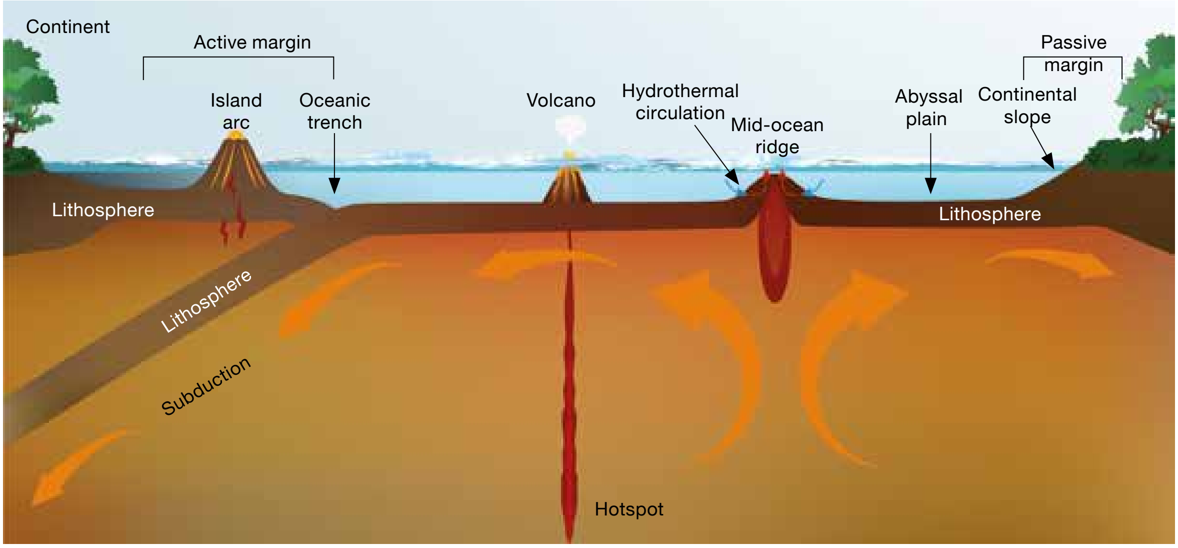

Fig. 1 – **Cross-section of the oceanic lithosphere.** © E. GODET. ■

Fig. 2 – **Volcanic pillow lava flow, at the Mid-Atlantic Ridge axis, at a depth of 3444 m.** ODEMAR expedition, *Pourquoi Pas?* oceanographic ship © Ifremer. ■

seabed. These hydrothermal fields are found along the ridges, and support extraordinary chemosynthetic biological colonies.

Passive or active continental margins

Between the ridges and the continental margins, the rigid plates migrate laterally, and progressively deepen as they cool. This is the uniform domain of the sediment-covered abyssal plains. The further they are from the axis, the older the plains, which reach depths of up to 5000 m. On a single plate, the transition with the continent is progressive. At these 'passive' margins, such as those around the Atlantic Ocean, a continental slope extending over several thousand metres connects the abyssal plains to the continental shelf.

However, when two plates converge, the denser plate descends beneath the other. This is the subduction phenomenon, which characterizes 'active' margins. The descending plate bends downwards to penetrate the mantle, forming a deep trench at the surface. Large oceanic trenches are therefore characteristic of convergent plate boundaries. In particular, they are found along the edge of the Pacific Ocean, where the plates formed at the East Pacific Rise move down beneath the American and Asian continents. The deepest trench, the Mariana Trench, reaches a depth of almost 11,000 m below sea level. As the descending plate penetrates, it creates friction. This triggers increasingly deep earthquakes as the plate moves downwards. It also leads to the production of magma, which feeds volcanic arcs: island arcs bordering the continents.

Oceanic islands and plateaus

The uniformity of the abyssal plains is broken locally by seamounts: large volcanoes formed by the action of fixed hotspots at the base of the Earth's mantle. These generate a magma plume, which rises to the surface, comes through the plates and spreads out over the seabed. As the plates move above the hotspots, these volcanoes tend to form alignments. The largest emerge to form oceanic islands, such as the Hawaiian island archipelago and the Society Islands archipelago in the Pacific, or Réunion Island in the Indian Ocean. The quantity of magma can be so huge that it creates gigantic undersea plateaus, such as the Ontong Java Plateau, which covers an area of 1.5 million km^2 to the north-east of Papua New Guinea.

The internal dynamics of the planet influence the ocean

The deep ocean floor is therefore largely shaped by the internal dynamics of the Earth. The vast abyssal plains correspond to the surface of rigid plates. However, the huge, continuous protrusion formed by the ridges impacts on oceanic circulation. Undersea volcanism and hydrothermal vents, generated by internal heat, emit fluids that influence the composition of seawater. The continental slopes are split by deep, winding submarine canyons, which act as conduits for sediment avalanches and water cascades, forming a connection between the coast and the deep seas. The earthquakes caused by subduction, most often occurring under the sea, can lead to devastating tsunamis. These can also be triggered by the slopes of large volcanoes collapsing, or by large landslides on heavily sedimented margins. An understanding of how the planet as a whole works is therefore essential for studying the oceans.

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20. The deep ocean: a mosaic of habitats

Pierre-Marie Sarradin and Jozée Sarrazin

The deep ocean is often defined according how far the sun's energy can penetrate. By this definition, it corresponds to depths of over 200 m. This environment represents 66% of the Earth's surface and over 93% of the biosphere. In the 19th century, the deep seas were described as a vast desert, and certain scientists even believed that there was no life there. It was not until we developed ways to access the deep seas and research submarines arrived in the early 1960s that this image changed. In 1977, the discovery of the rich ecosystems associated with oceanic ridges revolutionized our understanding of life on Earth: an alternative source of energy brought by reduced fluids, *via* microbial chemosynthesis, allows the deep seas to support abundant animal life, even without sunlight.

To this day, only a tiny percentage of the ocean floor has been explored, primarily thanks to surface operations conducted from research ships (cf. III.19) and, to a lesser extent, submersible dives (cf. III.8). However, we should remember that even today, the vast majority of the ocean floor (> 95%) remains entirely unexplored, and our knowledge of its biodiversity highly fragmented. In fact, it is not rare to collect a sample in which most of the species are unknown. Long limited to larger fauna (> 250 µm), studies on marine biodiversity are now increasingly interested in smaller fauna, notably including meiofauna (20-250 µm), the microbial compartment (1-5 µm), fungi (10 µm) and viruses (100-200 nm). Thus, 'just' inventorying marine biodiversity remains a huge objective. The international Census of Marine Life project (2010) counted 250,000 marine species. According to this evaluation, at the current pace of discovery, the oceans could contain 1 to 10 million species.

Since access methods were developed and explorations intensified, several new ecosystems have been discovered, giving the ocean floor a complex range of landscapes which are home to huge biological diversity, sustained by two major sources of energy.

Detrital ecosystems

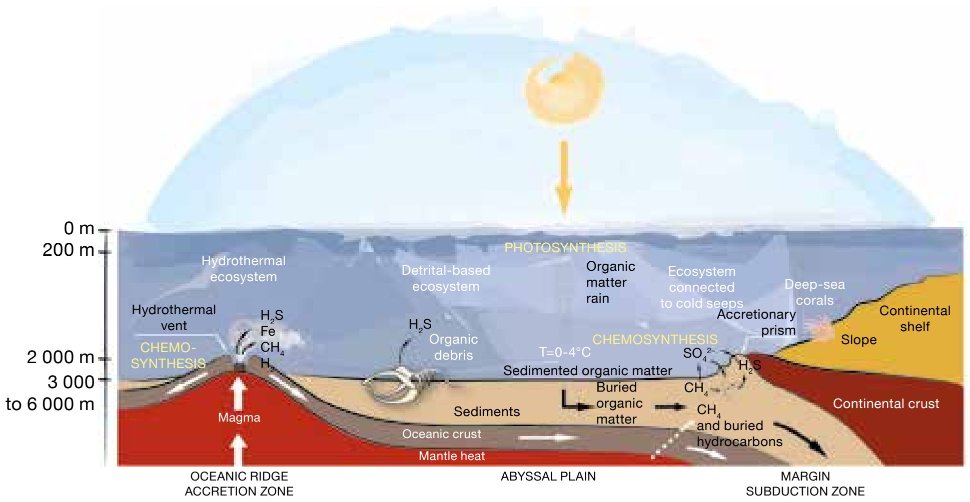
The seabeds are mostly covered with sedimentary abyssal plains. The fauna in this ecosystem relies on the detrital inputs from the surface, influenced by a seasonal dynamic which is connected to the variations in primary production in the photic zone. This fauna largely consists of small, burrowing organisms, which exhibit high diversity but low biomass, and are exploited by a sparse megafauna of deposivorous species.

Polymetallic nodules are present over vast zones of these abyssal plains, at depths of around 3000 to 5500 m. These rocky concretions measuring a few centimetres in diameter are composed of concentric circles of iron hydroxides and manganese hydroxides. A fixed fauna (corals, sponges...) develops on these hard substrates and uses the suspended food. The high microbial diversity of the nodules contrasts with that of the neighbouring sediments, and is thought to play a role in the metal mineralization process.

Cold water coral reefs are formed by cnidaria which have a skeleton. They are found in all oceans, at depths of 40 to 5000 m, and at temperatures below 14°C. They colonize hard substrates, such as carbonate mounds, seamounts and submarine canyons, as well as the ledges of the continental shelf, in areas characterized by strong currents. The reefs support great biodiversity and play an important ecological role by providing a complex structure which serves as a refuge, a feeding zone or a nursery for other organisms. Cold water corals are sensitive to human activities. Their slow growth rate and their long lifespan give them low resilience. They have been listed by several European or international bodies as threatened, vulnerable species or habitats.

Chemosynthetic ecosystems

Chemosynthetic ecosystems accommodate a different fauna to that found in the abyssal plains. Their main source of energy comes from microor-



The Deep Oceans: A Mosaic of Habitats. © Capsule Graphik/Ifremer. ■

ganisms which use the reduced chemical compounds brought by fluids to produce organic matter, *via* a process known as 'chemosynthesis' (cf. II.21). Most of the visibly dominant taxons ('engineer species') live in symbiosis with chemoautotrophic bacteria. Just like cold water corals, these foundation species play a major ecological role, by favouring colonization by other bacterivorous, grazing, carnivorous or necrophagous species. The fauna in these ecosystems is characterized by higher density and lower diversity than the fauna of the abyssal plains, as well as a higher rate of endemism.

Active hydrothermal vents are situated along mid-ocean ridges, in back-arc basins and near to undersea volcanic sites, to depths of over 5000 m (cf. II.19). Their specific composition varies from one region to the next, and the sites are colonized by an abundant fauna which is dominated by a small number of species. The habitats associated with active sites have contrasting physico-chemical properties, which contribute to the structuring of communities through their nutritional needs and their adaptations to extreme conditions. Hydrothermal systems are characterized by high temporal instability, connected to the underlying tectonic and volcanic processes.

Cold seeps are located on passive or active continental margins, and are associated with different geological structures (mud volcanoes, diapirs and pockmarks) which emit hydrocarbon-enriched fluids. Microbial consortia, situated in the top layers of the sediment, guarantee the anaerobic oxidation of methane and the production of hydrogen sulphide, which are necessary for chemosynthesis. The distribution of the fauna associated with these fluid emissions shows high spatial heterogeneity, particularly connected to the geochemistry, the flow of fluids and the substrate diversity (carbonates and sediments).

Whale carcasses and other massive inputs of organic matter provide transient habitats (lasting a few decades) for a series of organisms, starting with the arrival of necrophagous species. After several months, the breakdown of the organic matter by microorganisms leads to the production of hydrogen sulphide, supporting a chemosynthetic fauna which displays similarities with that of hydrothermal vents and cold seeps.

Finally, life is not only found at the surface of the ocean floor. With the discovery of microbial lifeforms up to 1700 m down in the sediments, the idea that there is a subsurface biosphere is now accepted. The extent of this biosphere is still largely unknown, because it is extremely difficult to access, but it is thought to contain the majority of life on Earth. Aside from the discovery of various ecosystems and of unexpected biodiversity, recent undersea explorations have helped to show the richness of deep sea resources. Be they biological, energy or mineral resources, they are increasingly sought after by industry (cf. V.12). The potential development of activities to exploit these resources requires us to first consider the impacts on these little-known ecosystems, so that we are better placed to prevent and limit damage, or even propose mitigation and restoration strategies (cf. VIII.6).

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21. Chemosynthesis: from abysses to mangroves

Nadine Le Bris

CO_2 fixation by the photosynthetic pathway is considered as the main source of energy for ocean ecosystems. However, sunlight is rapidly absorbed by marine waters and, at depths below 200 meters, photosynthesis is no longer possible. The organic matter produced by phytoplankton on the surface is gradually remineralized and only a small part of this resource reaches the obscure regions, which comprise 98% of the volume of the ocean (cf. II.20). As a result, the seabed is considered to be low in energy, especially in places where it lies far from the surface. But in reality this model is not totally relevant. Today, we know that alternative sources of energy are available in the ocean, and represent a mosaic of "chemosynthetic" habitats, in which communities of organisms proliferate through local production of organic matter. For example, deep hydrothermal vents or hydrocarbon seeps can harbor animal communities that are comparable to tropical reefs in terms of biomass.

Symbiotic activity

Deep-sea hydrothermal vents (cf. II.19), which were discovered on oceanic ridges 40 years ago, are emblematic of these environments, where intense microbial production fuels ecosystems identified as being among the most productive marine environments. Chemoautotrophic activity is supported by complex interactions between microorganisms, bacteria and archaea, and the environment chemistry. To date, six metabolic pathways that enable microbes to transform CO_2 into organic molecules have been identified. To 'fix carbon', these microorganisms exploit a variety of chemical compounds, whose reactions release energy. Hydrogen sulfide, abundant in hydrothermal fluids, is the main electron donor used. Its oxidation into sulfate using dissolved oxygen is one of the most energetic reactions available in the mixing zone of the hydrothermal fluid and seawater. Hydrothermal fluids are also rich in iron and dissolved manganese and sometimes in hydrogen, the oxidation of which is another major mode of energy acquisition. Another mode of carbon fixation is used by methanotrophs to produce organic compounds from the methane present in certain hydrothermal fluids, by exploiting the chemical energy of its oxidation.

The fauna that colonize these fluid emission zones therefore depend on these chemoautotrotrophic micro-organisms, and sometimes form close associations with them.

Fig. 1 – **Gills of a giant tubeworm capable of extracting the chemical compounds (CO_2, hydrogen sulfide, oxygen) needed by its endo-symbiotic bacteria.** © Ifremer / MESCAL expedition (UPMC-CNRS). ■

An increasing number of symbioses between invertebrates and one or several bacteria that develop on the surface or inside their host's organs, is being described in these environments. Beyond the emblematic giant tubeworms of the Eastern Pacific off Galapagos, where they were first discovered (Fig. 1), diversified families of bivalves, gastropods, and hydrothermal crustaceans that form symbioses with chemoautotrophic bacteria are now known. These ultra-specialized species and their multiple types of association reflect the optimal utilization of the sources of chemical energy available in environmental conditions that vary extremely over time and in space.

Fig. 2 – **Aggregation of mussels forming symbioses with chemoautotrophic bacteria associated with methane hydrates in a submarine canyon at a depth of 1,600 m, North American margin.** © Deepwater Canyons 2013 – Pathways to the Abyss, NOAA-OER-BOEM-USGS. ■

Unsuspected habitats

The enhanced exploration of the ocean floor in recent decades over regions of high heterogeneous tectonic and magmatic activity, beyond mid-ocean ridge axes, along volcanic arcs and continental margins, including in the most challenging regions of the Antarctic and the Arctic oceans, have progressively revealed the ubiquitous nature of these communities. These findings allow chemosynthesis to be integrated in a wider ecological context, which also includes submarine canyons from which sulfur-rich or methane-rich fluids seep, and faults where alkaline fluids rich in hydrogen and methane are formed by the interaction between seawater and the rocks that form the Earth's mantle.

More ephemeral habitats, such as massive organic substrates, wood or whale carcasses, also harbor communities that exploit chemosynthesis. The end products of organic matter degradation are indeed methane, CO_2 and hydrogen sulfide produced from the conversion of seawater sulfate. Such molecules may in turn serve as a starting point for a chemosynthetic trophic chain. These chemosynthetic symbioses are not limited to great depths. Chemoautotrophy is beginning to be identified as an important component in organic matter-rich marine ecosystems, such as mangrove forests, seagrass or upwelling regions associated with high planktonic productivity in surface waters. The diversity of these associations demonstrates the adaptability of benthic species to the variety of energy sources available *via* different electron donors (sulfide, methane, hydrogen) available, regardless of the geological setting (Fig. 2).

Characterizing the variability of environmental conditions remains a major challenge in deep-sea environments, where limited access to sites constrains monitoring over time. A few sites have benefited from more than 20 years of long-term studies. However, the functioning and dynamics of chemosynthetic ecosystems depend to a large extent on the relations between organisms and, often ephemeral, microenvironments, whose role in the ocean remains difficult to grasp, considering the great diversity of these systems. The extreme variability of physicochemical conditions (temperature, pH, oxygen sulfide toxicity...) and the instability of the habitat that accompanies these resources are essential keys to understanding the relationships that structure communities over time and in space.

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22. Ocean sediments

François Baudin and Eva Moreno

With the exception of underwater areas where basalt flows (oceanic ridges, seamounts...), virtually all ocean floors are covered with sediments of various origins, deposited in layers or successive strata. Neritic sediments are deposited at shallow depths (< 200 m), mainly under the influence of currents, while pelagic sediments result from the decantation through the water column of particles produced biochemically on the surface.

Sedimentation

The distribution of sediments in the present oceans reveals the predominance of different sedimentation modes (Fig. 1). Areas close to the continents, called margins, receive most of the particles transported by rivers. This input, called 'terrigenous', mixes with the particles produced on the platform (mainly limestone shells) to form neritic sedimentation. Rougher on the coast, neritic sediments become increasingly thin towards the open sea, with the exception of the zones of large deltas which can extend to the abyss by submarine deep sea fans, as at the outlet of the Amazon, the Congo or the Ganges. Polar reliefs are a particular source of terrigenous inputs, as the residues of their planing by glaciers are transported to the ocean by icebergs. These ice-rafted debris of any size are released when icebergs melt and mix with fine sediments to form heterogeneous deposits.

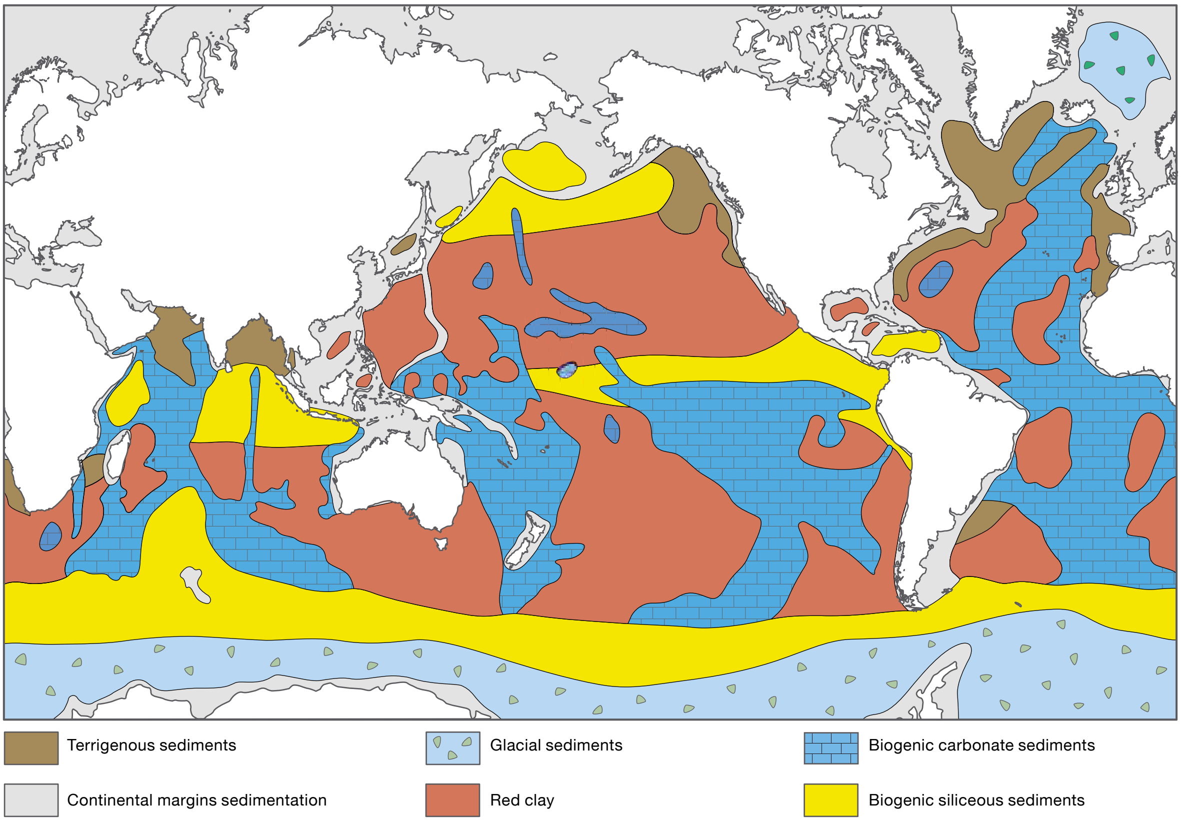

Fig. 1 – **Map of the distribution of the main types of sediments in modern oceans.** According to DAVIES and GORSLINE, 1976. ■

Fig. 2 – **Preparation of an ocean sediment core for the purpose of description and analysis.** © E. MORENO – CASEIS campaign the vessel *Pourquoi pas ?* ■

In open oceans, sedimentation is dominated by mineralized remains, also called 'tests', of plankton. Calcareous ooze consists of unicellular algae (coccolithophorids), protozoa (foraminifera) or micro-gastropods; siliceous ooze comes from algae (diatoms) or protozoa (radiolaria). From a general point of view, there is a link between surface primary production and the type of pelagic sediment. High production areas associated with sub-polar and equatorial currents correspond to siliceous sediments, whereas areas of low primary production correspond to carbonate sediments. However, chemical alteration affects these biominerals differently when they fall through the water column, which is cooled at depth and is enriched with dissolved CO_2. The calcareous tests are sensitive to these changes, which causes their dissolution. Slow down to a depth of 3.5 km, dissolution accelerates to a total depth of 'calcite compensation depth' (CCD), which is currently between 4 and 5 km. For siliceous planktonic tests, dissolution occurs in a completely different way. Very intense in the first two hundred meters, where nearly 80% of the biogenic silica is dissolved, it becomes negligible below a depth of 1 km.

Therefore, depending on the primary production and on the depth of the ocean floor, the nature of the sediments that rest on the bottom differs considerable. Carbonated ooze occurs between 60°N and 60°S near the ridges and down to a depth of to 4.5 km. Siliceous ooze is concentrated in high production belts. Diatomaceous mud is found on the bottom of the North Pacific Ocean and at the level of a peri-Antarctic belt, and finally radiolarian ooze is located at an equatorial belt in the Pacific and Indian Oceans. Outside these belts and below the CCD, where carbonates have been dissolved, even biogenic silica becomes unstable. Biogenous ooze gives way to the deep-bottom clay, a brown-red sediment, which has a triple origin: terrigenous with the finest fluviatile and aeolian inputs (desert dust and volcanic ash), authigenic, that is to say formed *in situ* (clays, oxides and hydroxides of iron and manganese), or cosmic with fragments of micro-meteorites. These red clays accumulate very slowly, at the rate of one millimeter per thousand years. In these very deep environments, especially in the Marquise-Hawaii-California triangle, polymetallic nodules accumulate on the bottom.

An archive of oceans and climate

Due to their slow accumulation in successive layers, pelagic sediments form a very precise archive that has recorded the changes in past oceanic conditions. From an oceanographic vessel, scientists can remove a portion, called a 'sedimentary core' from this succession (Fig. 2). With the current coring technology, it is possible to recover cores up to 60 meters in length, at depths of 4,000 meters. Other techniques, such as drilling, can penetrate sediment layers for more than 2 km. With this equipment, it is possible to study the climate changes and the brutal events that affected our planet during its history. Depending on the type of coring and the rate of sedimentation in the area studied, paleoceanographers can go back in time, from a few tens of centuries to nearly 170 million years, the age of the oldest oceanic floors.

The study of oceanic sediments has also provided evidence of lithospheric mobility in the emergence of plate tectonic theory. Indeed, scientists observed a symmetrical distribution of sediments relative to the axis of the ocean ridges. The farther from the ridge, the older the sediments in contact with the basalts. However, sediments older than 170 million years cannot be found because older oceanic lithospheres have all been recycled in the subduction zones.

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23. Seabirds

Sophie Bertrand and Christophe Barbraud

Although they make up just 3% of the world's bird species, seabirds are found across all oceans, from the poles to the Equator. The constraints of the marine environments in which they live have provoked remarkable morphological, physiological and behavioural evolutions in these species. Climate change affects this biodiversity in different ways according to latitude: an increased number of species in temperate and subarctic regions, but local extinctions in tropical regions. Global change also exacerbates the negative impacts of human activities.

In long-living vertebrates, responses to environmental fluctuations through phenotypic plasticity are faster than microevolutionary responses, and therefore represent the first line of defence in the face of a changing environment. Evaluating how far ecological niche plasticity allows species and communities to mitigate the effects of climate change is therefore crucial for maintaining biodiversity. This question is being studied by numerous research teams.

Tools for studying seabirds

First, scientists attempt to establish whether populations are increasing or decreasing. To do this, they conduct censuses either on the ground or using aerial photographs. Drones are also becoming increasingly important in this kind of monitoring. Models of population dynamics are widely used, given the difficulty of counting bird populations precisely, everywhere, at every moment. To configure these models, researchers work on the ground to document the levels of reproductive success and identify birds by banding them, so that they can estimate lifespan, survival rates and fidelity to reproduction sites.

Fig. 1 – **Masked booby and artisanal fishing boat, Fernando de Noronha archipelago, Brazil.** © K. DELORD. ■

Next, to find out what the birds eat, in terms of quantity and quality, there are two types of approach. The first involves examining their stomach contents, in order to identify otoliths (small bones from the heads of fish), for example. These can be used to recognize the species consumed and count the number of prey. The second approach involves analysing isotope ratios (carbon, nitrogen or mercury) in the blood or feathers of birds, which can be used to trace the type of prey that the bird has consumed in recent months or weeks.

Finally, we need to know which zones the birds rely on for food. This field of research has undergone major developments over the last 30 years, thanks to technological advances, which have allowed the miniaturization of many measurement devices. Today, certain birds are equipped with GPS, accelerometers, dive recorders or video cameras to track their journeys at sea.

Fig. 2 – **Red-footed booby chick, Fernando de Noronha archipelago, Brazil.** © S. BERTRAND. ■

Interactions with fishing

Fishing can interact with sea birds in many ways. The first and most visible is birds being accidentally caught by fishing gears. Seabirds live a long time and have low reproduction rates, so the survival of adults only needs to drop by a few percent for populations to decline. The extent of this problem became apparent for the first time in the 1970s, when research showed that several hundred thousand birds were being killed accidentally every year in driftnets, which were subsequently banned in 1990. However, offshore fishing activity then transitioned to longline fishing. It is now albatrosses, petrels and another similar species that are accidentally caught.

As well as affecting the survival rate of adults, bycatch can exert pressure on the population in the form of evolutionary selection. Using models of population dynamics, researchers have found an explanation for the rise in the wandering albatross population on the Crozet islands. These birds can present different phenotypes in terms of their behaviour: some are more aggressive and forward, others more timid and less curious. Consequently, they do not all display the same attraction and behaviour towards fishing boats. The more curious birds are at greater risk of being accidentally caught, so their population decreases. Fishing therefore exerts real evolutionary pressure, resulting in the selection of certain individuals. This may appear advantageous in the short term, but we need to consider which evolutionary resources have been lost with the curious individuals.

Fishing may have more unexpected consequences for bird populations. In South Africa, faced with the decreasing population of their natural prey (small pelagic fish targeted by a purse seine fishery), cape gannets have learned to take advantage of the 'easy' food provided by discards from trawlers. Unfortunately, the fish species discarded by trawlers have far less nutritional value than the small pelagic fish, and the colonies forced to feed their young on this 'junk food' have higher chick mortality.

The third type of interaction that fisheries may develop with birds is that of direct competition for prey. For birds, the reproduction period is the most critical period in energy terms, because parents need to feed their chicks, as well as themselves. Meta-analysis (14 species in 7 ecosystems) has shown that when the abundance of prey fish is lower than a third of its historical maxima, the reproductive success of the birds plummets. The overall competition between birds and fishermen to get their share of the prey can also be exacerbated by local exhaustion effects. Birds need plenty of prey when raising young, but this must also be available near to the colony, because young chicks cannot survive the prolonged absence of their parents. In Peru, bird populations are in direct competition with the seine fishery for anchovies. A study has demonstrated that the opening of this fishery modified the birds' behaviour at sea, causing a significant increase in the effort needed to feed their chicks. In the small zone studied, the fishery was taking 250 times more anchovies per day than the birds! Therefore, even if the total quantity of anchovies had been enough for the birds that year, the local exhaustion effects meant that the prey was not necessarily available to the birds.

Situated at the top of the food chain, sea bird populations integrate the fluctuations in the ecosystems that they occupy, making them true indicators of the effects of global change in marine environments. It is therefore essential to study them, both for the conservation of their species, and for the insight they give us into the mutations currently sweeping through marine ecosystems.

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24. How oceanographic processes influence sea turtle distribution

Damien Chevallier and Yvon Le Maho

Turtles have been present on our planet for 110 million years and are found in all the oceans, from warm tropical waters to the cold waters of the Arctic. The seven current species are under threat of global extinction and are therefore included in Appendix 1 to the Washington Convention and are on the Red List of the International Union for Conservation of Nature. Incidental catches of sea turtles by fisheries are responsible for a considerable number of deaths. In addition, there are impacts from turtle poaching, despite their status as a protected species, and the degradation of the marine habitat and nesting sites. Overall, incidental captures, the degradation of habitat, human consumption of turtle meat and eggs and the sale of their shells have dramatically reduced sea turtle populations throughout the world. As iconic species of endangered biodiversity and fundamental components of ecosystems and the dynamics of natural resources, sea turtles are a major priority in terms of the sustainable management and preservation of marine ecosystems. They are also an important asset for promoting biodiversity, particularly on the economic front, because of their tourist appeal.

Fig. 1 – **Olive ridley sea turtle in French Guiana fitted with an Argos GPS transmitter.** ■

Tracking their movements

Turtles are amongst the most impressive navigators in the animal kingdom, following migration routes that sometimes cross entire ocean basins. Most species of sea turtle can migrate considerable distances between their foraging sites and their breeding and nesting grounds. Other than in the breeding season, when the females lay their eggs on the nesting beaches, it is difficult to observe turtles in their marine environment, especially since this can span thousands of miles. The diversity of the physicochemical characteristics of the high seas and the seasonal and interannual variability in the climate (cf. II.11) make these waters a heterogeneous environment. This complexity is reflected in inequalities in resource production in space and over time and therefore in the dispersion of resources. As a result, distinguishing the factors that determine turtle distribution at sea and understanding their foraging strategy in response to changes in oceanographic conditions and climate variability involve major challenges that span the dividing line between oceanography and ecology.

Until very recently, knowledge of how different species of sea turtles develop and forage in their dynamic environment was still rudimentary. However, the development of spatial technology and the constant progress in micro-electronics and information technology have now made it possible to understand how turtles optimize their movements depending on the location of their breeding sites and their food sources.

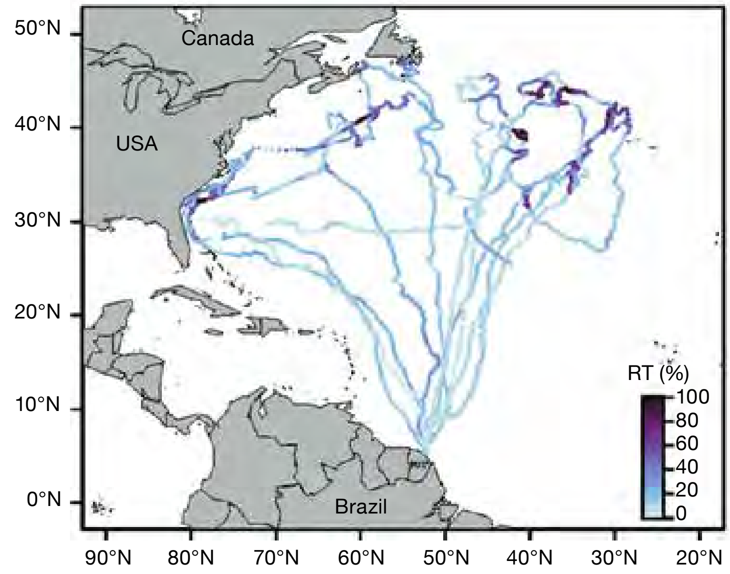

Fig. 2 – Satellite tracking of 10 leatherback turtles starting from French Guiana. ■

Links between the environment and behaviour

To understand how oceanographic and biological conditions determine leatherback turtles' migration routes from their nesting sites to their foraging sites at sea, researchers needed to analyse their trajectories and their diving behaviour. The turtles therefore had to be fitted with miniature trackers (Fig. 1), to capture detailed information about both their foraging behaviour and their marine environment, right across the oceans (cf. III.13).

To this end, leatherback turtles coming ashore to nest were fitted with Argos transmitters, so that their post-nesting migration could be tracked. The experiment enabled a connection to be established between: *i)* the turtles' horizontal movements and physical gradients (temperature, irregularities in the depth of the water and currents) and biological variables (micronekton and chlorophyll-a); *ii)* their diving behaviour and the water column structure (comprising the mixed layer, thermocline, halocline and nutricline). All turtles migrated north, in the direction of the 'wall' of the Gulf Stream (Fig. 2). Using a combination of information from the tracking of individual tagged turtles and ocean satellite data, the importance of the Gulf Stream frontal system in leatherback turtles' selection of foraging zones was evaluated for the first time. Although the foraging areas were geographically dispersed, with locations between 80-30°W and 28-45°N depending on individual animals, all the turtles targeted similar habitats in terms of physical structure, *i.e.* they had steep sea temperature and surface-depth gradients, and a deep mixed layer. This strong association with the Gulf Stream frontal system highlighted a synchronism. Turtles stayed in the enriched mixed layer at depths of around 40 m when diving in foraging zones where they were likely to have easier access to their prey, thereby maximizing the energy gain. These were shallower depths than they reached in the thermocline (~80 m) when crossing the nutrient-poor subtropical gyre, probably to get to cooler water and save energy during their post-nesting migration.

Understanding how this frontal system influences leatherback turtles' behaviour is crucial for the conservation of this vulnerable species, particularly in the North Atlantic, where the huge lethal impact of fishing is an ongoing concern.

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25. The fate of the coral reefs

Serge Planes

Like the tropical forests, coral reefs are biodiversity hotspots, their lush natural environment often serving as an example when referring to biodiversity conservation. According to current estimates, the coral reefs are home to 30% of marine fauna and flora, even though they only cover 0.2% of the oceans' surface (Fig. 1). In addition, coral reefs form coastal barriers, protecting the inhabitants of tropical coasts during storms and cyclones, and are an invaluable source of income in the economies of many developing countries.

Again, like the forests, the coral reefs are suffering severe decline. Nearly 25% of coral reefs have allegedly disappeared over the last 20 years and around 50% are in a critical state now. The coral reefs are particularly affected by global change and subject to anthropogenic pressures specific to coastal ecosystems. They urgently need to be managed in a more sustainable manner, firstly by better integrating knowledge in their governance.

Biodiversity still largely unknown

Coral development depends on endosymbiosis with a single-celled alga, zooxanthella, which has been the subject of several studies over the past couple of decades, for example to further understanding of its energy input. In the 1980s, researchers demonstrated the existence of multiple zooxanthellae clades with different ecophysiological performances. This diversity may be the factor underlying coral's ability to adapt to environmental changes. The development of genomics and high-speed sequencing capacities guide current research into the molecular basis of gene expression and its variability under different kinds of stress, such as rising ocean temperatures, acidification or excessive sedimentation from rivers and deforestation.

Coral bleaching, a striking phenomenon that receives much media attention, is caused by stress that puts an end to symbiosis in the coral, which digests or expels the zooxanthellae. The cellular and molecular mechanisms that cause symbiosis to break down are currently the subject of many research projects.

This complexity, apparent at the very foundations of the ecosystem, is a constant that is inherent to the coral reefs. As a comparison, 1 km^2 of coral reef contains as much diversity, in

Fig. 1 – Diversity of a coral reef in Moorea, French Polynesia. © L. THIAULT. ■

terms of species numbers, as mainland France, which explains why a succession of ministers for Overseas France have insisted that French biodiversity is mainly found in its tropical territories. This microbial biodiversity is almost infinite and still largely unknown. It is a source of chemical diversity that is subject to fundamental research in the field of chemical ecology, and applied in the marine biotechnology sector (cf. V.12).

Research into the coral reefs

Symbiosis is not the only phenomenon at work in the coral ecosystem. It is also affected by habitat fragmentation, heightened in the island shore habitats in the Pacific, the Indian Ocean and the Caribbean. It can also be seen on coasts (*e.g.* on the Australian Great Barrier Reef), due to the geomorphology and stenohaline limits of corals. This fragmentation makes the entire ecosystem more fragile and the phenomenon has been covered in several studies on larval connectivity in the coral reefs over the past couple of decades. These studies have enabled significant advances with wider repercussions for marine habitats, with models emphasizing a reduced context for the dispersing pelagic larval stages when compared to previous conceptions.

Social and human sciences need to be added to this ecosystem physiognomy to allow a broader approach, known as 'conservation biology'. In such a context, research into coral reefs clearly provides some unique examples, such as the very large marine protected areas of the Great Barrier Reef, New Caledonia, Kiribati (cf. IV.15), Hawaii or the Chagos islands, with management systems that integrate the concepts of usage and traditional knowledge combined with an evaluation of ecosystem services and the prospect of payments *via* trust funds. In this area, studies on the coral reefs will be able to construct overall approaches that will undoubtedly influence the shape of future conservation policies.

Fig. 2 – **Bleached corals in Samoa in 2016.** © P. MARSHALL. ■

On the research front, in many respects the coral reefs now find themselves at a critical stage and their fate as an ecosystem is more fragile than ever. The last two years (2015–2017) were marked by major bleaching events across the Indo-Pacific basin, the result of global warming (Fig. 2). In some parts of the Pacific, mortality exceeded 50%. With that in mind, recent predictions have been somewhat pessimistic, stating that by 2040, the coral reefs will undergo annual bleaching events and suffer significant mortality.

We should not despair, however. Although they will be less rich in biodiversity and certainly less attractive, the coral reefs will not disappear altogether. As Erik Solheim, Executive Director of the United Nations Environment Programme points out '*These predictions allow conservationists and governments to prioritize the protection of reefs that may still have time to acclimatize to our warming seas.*'

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26. Mangroves of the tropical coasts

François Fromard and Antoine Gardel

Mangroves develop on almost 75% of tropical and intertropical coasts. Faced with harsh constraints (the tidal cycle, the salinity of the waters and the instability of the substrates), mangrove ecosystems are characterized by low plant diversity and the remarkable adaptation of woody, habitat-dependent species: mangrove trees. Unusual root systems provide effective anchorage for the trees (the stilt roots of the Rhizophora) and allow continuous respiratory exchanges in all tidal conditions (the pneumatophores of the Avicennia et Sonneratia). Processes of filtration in the roots and excretion through the leaves (disposal of salt crystals *via* specialized glands in the leaf surface) allow the plants to regulate excess salt. The buoyancy and viviparity of the mangrove tree propagules allow rapid dispersion and growth. Moreover, mangroves are closely dependent on the adjacent environments, with tidal flows and river currents providing direct connectivity between the freshwater masses of the catchment basins and the coastal waters. Mangroves are also characterized by high resilience, allowing quick recovery after a disturbance, if the hydrodynamic context allows it.

In connection with these characteristics, mangrove ecosystems provide many documented ecological services. Their role in protecting the coasts has been recognized during cyclonic events (Sri Lanka, Burma, Indonesia), where human and material losses were limited only in areas protected by undamaged mangrove. Mangroves are also a habitat for many marine species (fish, shrimp, crabs), which feed and reproduce there. However the direct connections between rich coastal fish resources and the presence of mangroves are still not clearly established. Conversely, the role of mangrove in trapping pollutants and sediments has been characterized and incorporated in bioremediation projects. Its function as a carbon sink (associated with its high productivity) is now proven, and the scale of the carbon input into the oceans has been quantified: it is thought that 15% of oceanic carbon comes from mangroves. This ecosystem should therefore be considered highly influential for global carbon flows (cf. II.14).

Fig. 1 – **Mangrove area in the Oyapock estuary, French Guiana.** Between land and sea, mangroves can withstand the currents and waves. They advance or recede according to the natural processes of erosion and sedimentation. A sea level rise would quickly disrupt this fragile equilibrium. © F. FROMARD. ■

However, mangroves are severely threatened by humans, and are receding due to direct pressures. Mangrove ecosystems are also among those most affected by climate change, which is already harming their integrity locally.

The vulnerability of mangrove ecosystems

The heavy anthropic pressure on the coasts has led mangrove forests to recede significantly in many countries. Although Southeast Asia has the largest area of mangrove (33% of the world's mangroves), it is also here that this ecosystem has receded the most. This is primarily due to shrimp farming, since mangroves are cleared to create shrimp breeding ponds (in Vietnam, Indonesia and the Philippines). The dams upstream of the mangrove forests restrict the freshwater inputs needed for the ecosystem to function, and the coastal dykes upset the coastal dynamic. This has caused massive die-back of the ecosystem in several countries (Mozambique, Pakistan, etc). Furthermore, oil operations, which entail pollution and clearing, are the primary cause for the degradation of one of the largest mangrove areas in the world, in the Niger Delta. Consequently, there was a 20% drop in the surface covered by mangroves between 1980 and 2005, equating to a decrease of almost 1% per year. Recognition of the ecological services rendered, protection initiatives and carbon offsetting schemes are now slowing this decline, although situations vary widely between countries.

Mangroves and climate change

Rising sea levels can directly affect mangroves associated with the intertidal zone. On the Mexican Pacific coast, mangrove forests have receded on the coastal fringe, but are developing further inland as the sea level rises. Identical phenomena have been observed for small island mangroves. Meanwhile, in the Bay of Bengal, the huge Sundarbans mangrove forest is receding under the combined effects of subsidence (collapse of the sedimentary basin) and rising sea levels. Predictive mangrove distribution maps have been proposed, based on different rising sea level scenarios, showing various mangrove responses in different regions.

Fig. 2 – **Europa Island mangrove, Indian Ocean.** The stilt roots of the red mangrove tree (*Rhizophora mucronata*) provide it with firm anchorage in an often unstable environment. © F. FROMARD. ■

Mangrove development at the North and South boundaries of the zone is controlled by the sea's surface water temperature, with the winter position of the 20°C isotherm corresponding to its current boundary in both hemispheres. The recurrence of extreme cold is also a major regulating factor for the longitudinal expansion of mangrove forests. In the current context, with these events becoming less frequent, mangrove expansion can be observed at both the northern (Louisiana, Florida) and southern (New Zealand, South Africa) boundaries of its zone.

One of the hypotheses adopted regarding climate change is that of decreased precipitation on the margins of subtropical regions. Moreover, it has been proven that equatorial mangroves are more productive than those in arid regions, and that although mangroves are adapted to the salinity of the coasts, too much salt restricts their growth. Decreased precipitation would lead to increased salinity in the substrate of the mangroves, hinder their productivity, and cause them to recede in the areas concerned. These processes have been observed in Australia, where almost 10,000 ha of mangrove have recently died off due to drastically reduced precipitation in the preceding years. Similarly, mangroves at the arid boundaries of their zone (Persian Gulf, Red Sea) are threatened today by decreasing rainfall.

The French overseas mangroves (100,000 ha) are subject to various direct anthropic pressures, which are severe in Mayotte and the Antilles, and mild in French Guiana. Current research in these regions, as well as in New Caledonia or the Scattered Islands, aims to highlight the ecosystem services rendered, characterize their evolution in a changing climate context, and encourage their conservation or restoration.

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CNRS

- PART THREE -

Exploring the ocean

Previous page:

Traps used to collect plankton. VAHINE mission in New Caledonia. © IRD / J.-M.BORÉ. ■

1. Exploring the ocean

Catherine Mével, Laurent Bopp, Pascale Delecluse,
Françoise Gaill and Catherine Jeandel

The ocean is not humankind's natural habitat but it plays a fundamental role in our lives and influences our environment. It is essential that we describe it, understand how it works and are able to predict its future evolution. For a long time, exploration techniques adapted to the marine world only provided fragmented, sketchy data due to the immensity and hostility of the environment. However, since the mid-20th century, considerable technological breakthroughs have enabled huge progress in the observation of this environment. At the same time, an equally significant advance in theory – in the field of geophysical fluid dynamics, for example – has made it possible to link observations to a relevant conceptual framework.

Modern oceanic fleets fitted with high-performance systems are used to observe, measure and take samples, thus letting us further our knowledge of surface waters and the sea floor, of the water column that lies in-between, and of the living species that thrive there. Oceanographic campaigns include bathymetric surveys and geophysical studies of the sea floor, measurements of the physical and chemical parameters of the water column using sophisticated sensors, and water, rock and organic samples. While manned submarines remain the best way of exploring the ocean's depths directly, easy-to-use, high-performance remote-controlled robots are now used in all marine environments. Oceanographic campaigns traditionally bring together specialists from across the scientific spectrum with physicists, chemists, biologists, fishery scientists and ecologists, geologists and geochemists working side-by-side on ships and pooling their expertise.

Since the early 1990s, the use of satellite data has revolutionized the study of the ocean, enabling measurements to be repeated over time in the different oceans of the world. Satellite measurements were used to produce the first world map of ocean floor relief. Satellites are also used to measure sea level, temperature and the colour of water from space. At the same time, continuous measuring devices are now used in an *in situ* network of drifters (at the ocean surface) or profiling floats (in the water column), instruments placed on the sea floor, mooring gear and miniature sensors to monitor marine megafauna.

All these observations, measurements and samples feed into the research conducted by scientific teams. The data obtained in the field or in the laboratory may be used in digital modelling to broaden understanding of the processes under study. Ocean modelling also simulates the evolution of the environment in response to human disturbances. Increasingly, researchers work within a European or international framework and there are ongoing efforts to standardize measurement protocols and sampling to facilitate data exchanges. The *Tara* project is one remarkable example: it is based on a schooner, recalling the 19th century expeditions, yet applies the very latest techniques.

The current concept of ocean exploration combining every kind of *in situ* measurement satellite observations and digital modelling. © G. GORICK / GOOS. ■

2. Observing the oceans

Philippe Bertrand

Knowledge of the ocean involves several disciplines (physics, chemistry, biology, social sciences and economics) and a considerable range of space and time scales, from local processes taking less than one day to regional processes lasting anywhere from a season to 10 years; and from global ocean circulation (spanning 10^2 – 10^3 years) to the evolution of species (10^6 – 10^8 years) and the evolution of the Earth system (> 10^8 years). As a topic of research, the ocean is therefore too complex for traditional inductive theory to be of use. Understanding of the ocean can only be developed through deductive observation, where metrics are used to produce models for assessment of other real-life situations to check that our understanding is sound and for making forecasts.

Observations differ, however, depending on the purpose of the research, ranging from targeted campaigns which aim to provide a precise description of a situational snapshot (cf. III.19), to distributed networks or satellite observations that help in understanding the dynamics of large space-scale phenomena over periods of more than a few decades.

Campaign-based observation

One of the first human concerns in exploring the ocean was marine life in all its forms. The dual status of the sea as a source of legends and curiosity led plenty of scientific explorers to plough the waves in order to report their observations of the 'peoples of the sea'. Two such examples are Darwin's diary entries relating the voyage of the Beagle in 1839 and John Steinbeck's tale of his expedition on the Sea of Cortez aboard the Western Flyer in 1940. More recently, the progress in genomic analysis has enabled such explorations, like *Tara* Oceans from 2009 onwards (cf. III.6), to take a quantitative approach to the question of marine biodiversity, from viruses to algae and higher animals. This work resulted in the award by the French National Centre for Scientific Research (CNRS) of its Medaille d'Or to Éric Karsenti in 2015.

Soon, though, explorers also began to take an interest in many non-biological matters: bathymetry, seabed topography, volcanic and hydrothermal activity, currents, tides, internal waves, temperature, salinity, chemistry, and so on. Hydrographic data was collected on pioneering expeditions such as those led by Scott, Amundsen, Shackleton, Charcot and Albert I of Belgium in the 19th and 20th centuries. In the 1970s, French and American expeditions des-

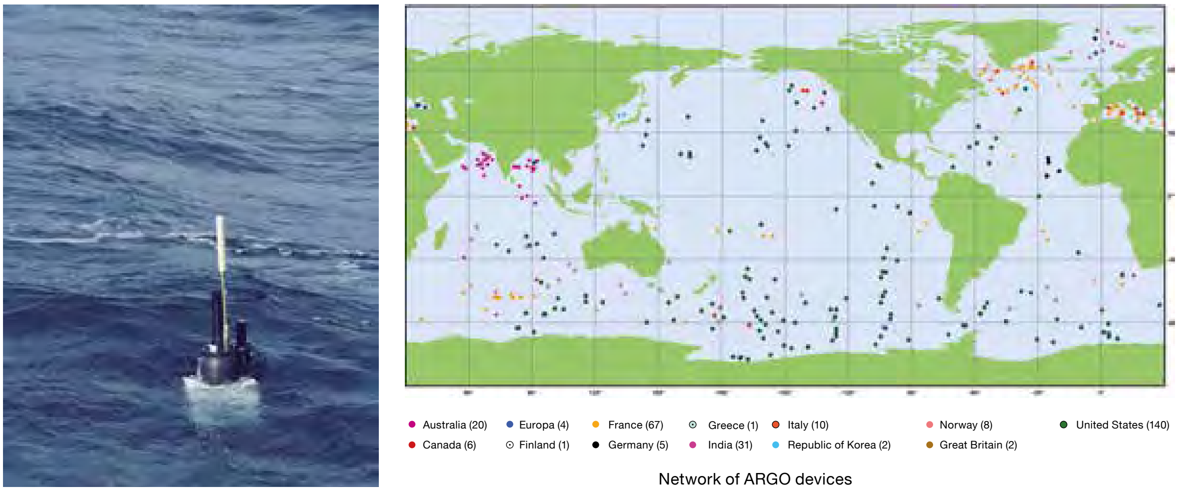

Fig. 1 – **Photo of an ARGO biogeochemical profiling float at the surface (© G. OBOLENSKY / LOV) and location distribution map for the ARGO programme's biogeochemical profiling floats as at February 2017.** ■

cribed the undersea evidence of ocean formation (such as the Mid-Atlantic Ridge) and laid the conceptual foundations of plate tectonics, which then replaced continental drift.

Observing the global ocean

High-sea expeditions provided an understanding of the ocean as an essential component of the climate. Surface currents redistribute thermal energy and salt from low to high latitudes. As water's density is determined by its temperature and salinity, this redistribution contributes to the formation of dense water which then sinks and circulates at depth, thereby initiating the convection cycle or general thermohaline circulation (cf. II.11). The ocean also influences the greenhouse effect, releasing CO_2 emissions into the atmosphere in certain regions and pumping CO_2 into the sea in others. The overall result of these exchanges is that CO_2 is removed from the atmosphere, because of the sinking of dense water masses and the waste from biological production of the ocean. We now need to know in more detail how these mechanisms affect the sea's interaction with global and regional variations in climate; this requires data from a number of frequent, widely distributed observations. This is the reason that global observation systems were introduced and are being expanded. They are coordinated as part of the international framework for ocean observation utilised by GOOS (the Global Ocean Observing System) and include both *in situ* and satellite observations. Since 2000, the ARGO programme has deployed thousands of drifting 'profilers' which take measurements every 10 days between the surface and a depth of 2,000 m, and the aim is to reach 4,000 m. Satellite observation also makes a major contribution to global observation of the ocean, providing altimetry images (from the TOPEX/Poseidon mission in 1992, then the three Jason satellites, SARAL/AltiKa and the SWOT project) and colour images (from the MERIS, MODIS, SeaWiFS, VIIRS and OLCI satellites). Some of these spatial imaging initiatives involve the development of operational services to support public sector decision-making (the information services provided by the European Copernicus programme are an example of this).

Fig. 2 – **Satellite image of the Gironde estuary, France, taken on 18 February 2017 by the MultiSpectral Instrument (MSI) sensor on board the ESA Sentinel-2 platform.** The variations in the colour of the water make it possible to identify the areas of maximum turbidity. Source: www.highroc.eu. ■

Observing the coastal ocean

Coastal zones present different intrinsic characteristics, hazards, risks and vulnerabilities. For research purposes and for public sector or socio-economic decision-making, they therefore require an observation strategy that reflects the pressures from the high seas (swell, fetch, internal waves, currents, local sea level and sea surges) and from catchment areas (soil conditions, habitats, industry, flow rates, floods, pollution, and sediment and dissolved element flux), and local measurement of the impacts, on the coastline, morphodynamics, ecology and ecotoxicology. For example, France's national coastal environment observation service (SOMLIT), set up by 10 marine observation stations, has spent more than 20 years acquiring low-frequency (bimonthly) standardised data on the hydrological and biological characteristics of coastal waters. High-frequency data corresponding to a more limited set of parameters is acquired by another system using automated buoys (COAST-HF). Coastal zone observation also demands international action, on the technological harmonisation of measurement strategies (encompassing sensor types and locations and data acquisition intervals), on impact analysis in response to global pressures, and on interoperable data management. This process is less advanced than for the high seas, because of the much greater diversity of data and coastal approaches. Efforts are nonetheless underway in France and at European level.

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3. How satellites contribute to ocean observation

Pierre-Yves Le Traon and Bertrand Chapron

Long-term observation of the oceans is a necessity for better characterization of climate change, for understanding and predicting the role of the ocean in climate, and for making informed political decisions on measures to mitigate and adapt to climate change. It is also essential for services and applications in operational oceanography.

Regular global observation of essential ocean variables

Satellites have revolutionized our ability to observe the oceans. Satellite oceanography uses two main techniques: passive techniques (radiometry), which measure the natural electromagnetic radiation emitted by the ocean's surface or reflected solar radiation; and active techniques (radar), which consist of emitting a satellite signal and analysing the signal received after it is reflected at the surface of the ocean.

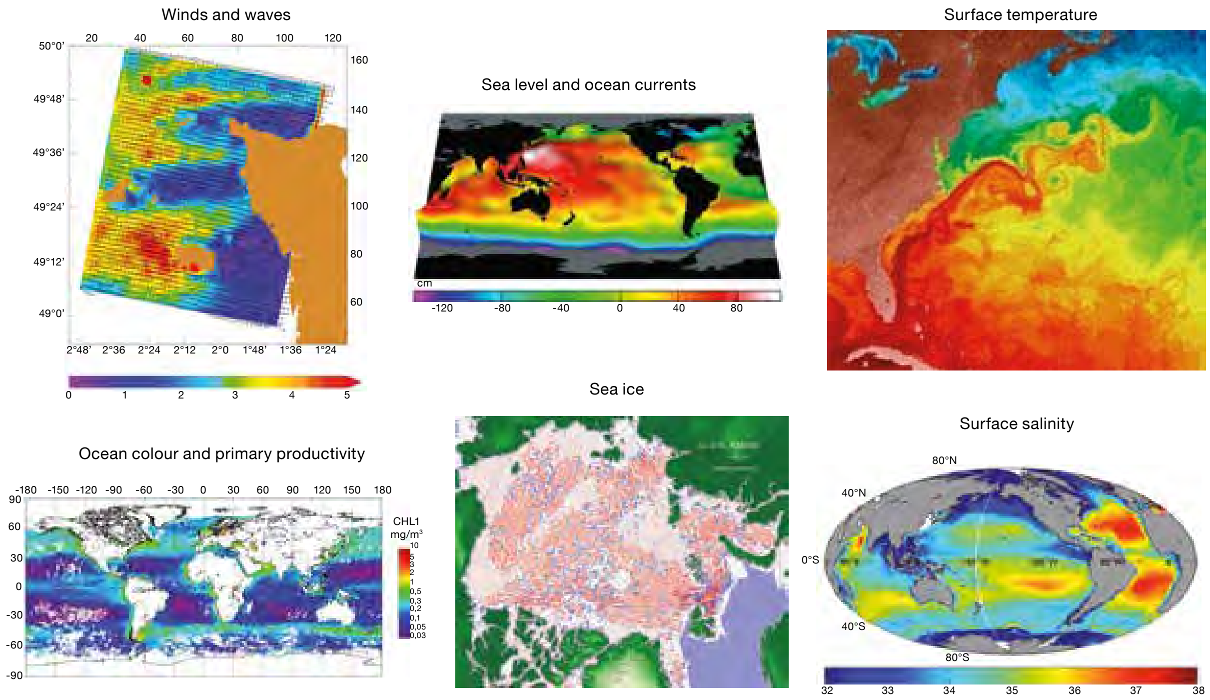
In both cases, isolating the signal from the ocean requires the transmission of the signal through the atmosphere and emission from the atmosphere itself to be taken into account. Based on the intensity, frequency distribution and polarization of the radiation emitted or reflected at the surface, the characteristics of the ocean's surface can be estimated.

Satellites now provide routine access to observations of ocean variables that are essential for the study of the oceans and climate: sea level and major ocean currents (using altimetry); surface temperature (*via* infrared or microwave radiometry); the concentration, thickness and drift of sea ice (with microwave radiometry, altimetry, diffusometry and synthetic aperture radar/SAR); the concentration of phytoplankton and suspended matter (based on the ocean's colour); waves (with SAR and altimetry); winds (microwave radiometry, diffusometry and SAR); and more recently, surface salinity (using microwave radiometry).

Satellites today provide a regular, near real-time holistic view of all the oceans – the basis of their tremendous contribution to the global ocean observing system. In-situ observations remain essential, however, for calibrating and validating satellite observations, but first and foremost for providing crucial complementary information of the interior of the oceans. Satellites make an even greater contribution when used in conjunction with *in situ* observations.

Major advances using satellite altimetry

Satellite altimetry, a French sector of excellence, occupies a unique position amongst the remarkable advances in satellite oceanography over the last few decades. The continuous and markedly accurate measurements of sea level and geostrophic currents provided first by the TOPEX/Poseidon satellite mission and then by Jason-1/2/3, have enabled major advances in our understanding of the climate and the ocean. Changes in average sea level and the geographic variations of the seas have been accurately described (cf. II.15). Altimeter satellites have also been used to characterize and provide real-time monitoring of the development of the El Niño and La Niña phenomena (cf. II.13). More generally, altimeter measurement



Observation of the oceans: contribution of satellite techniques. The figures above illustrate the contribution from satellites for the observation of essential ocean variables. Source: Ifremer. ■

of sea level places strong constraints on the ocean analysis and forecasting systems used for operational oceanography and its applications (cf. III.12). Monitoring ocean circulation (including mesoscale eddies) requires permanent coverage of the ocean with several altimeters. For over 20 years, the ERS-1/2, ENVISAT and SARAL/Alti-Ka satellites complemented the observations provided by TOPEX/Poseidon and Jason. Provision of complementary data continued with the Sentinel-3A and B missions under the European Copernicus programme, an ambitious long-term Earth observation and surveillance programme. Copernicus also includes a follow-up to Jason-3 for the period from 2020 to 2030 (Jason CS or Sentinel-6). The SWOT satellite scheduled for launch in 2021 is expected to lead to further advances by making it possible to take finer scale measurements using wide-swath altimetry.

Challenges for the future: continuity of measurements and new technologies

Satellites make an essential contribution to the study of the oceans and the climate. The challenges now are to ensure the long-term monitoring of a series of essential ocean variables, as well as observing the oceans in more detail and at a higher resolution with the contribution of new satellite technologies. In parallel, it is essential to ensure that *in situ* observation systems are enhanced.

Increased cooperation between the space agencies will be necessary both for optimizing and combining the coverage of the different missions (creating a virtual satellite constellation) and for ensuring that the measurements from the various satellites are intercalibrated and homogenized. France and Europe play an important role in this cooperation, through the Copernicus programme in particular.

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4. Observing the oceans: the argo revolution

Pierre-Yves Le Traon

The oceans store and transport enormous quantities of heat, water and gas, which they exchange with the atmosphere. These exchanges have a major influence on the global and regional climate, over time-scales ranging from a few days (storms and cyclones), to seasons (monsoons), to several years (El Niño) and even several centuries (global warming). Over the last 50 years, the ocean has absorbed over 90% of the excess heat received by the planet, due to the increasing concentration of greenhouse gases in the atmosphere (cf. II.10). A precise understanding of the ocean and of the long-term global observations is essential for characterising the effects of climate change, and for understanding and predicting the evolution of the planet's climate. It is also indispensable for the applications and services of operational oceanography.

The Argo international programme

Launched in 2000 by the Intergovernmental Oceanographic Commission (IOC) and the World Meteorological Organization (WMO), the Argo programme is a global array of almost 4000 autonomous profiling floats measuring the temperature and salinity of the upper 2000 m of the ocean in real time, at 10-day intervals. Argo is the fruit of outstanding international cooperation, with more than 30 countries directly involved in setting up the array. Every year, around 900 instruments are deployed: this is the number needed to maintain a fleet of 4000 active floats, given their estimated life of 4 to 5 years.

An Argo float is a small, autonomous, underwater instrument. These floats are preprogrammed, then deployed from oceanographic research vessels or ships of opportunity. Once launched, they run on ten-day cycles for several years, until their batteries are flat. Each cycle includes a descent lasting several hours, to a depth of 1000 m, where the float drifts for around 9 days. Then, it descends to 2000 m. From this depth, it starts an ascent profile by sampling the temperature and salinity every metre until it reaches the surface. The data are then transmitted to the processing centres, in real time and by satellite (Argos and Iridium).

Argo is the first global, real-time, *in situ* oceans observation network, and it marks a true revolution in the global observation of the oceans. The Argo observations complement the more exhaustive observations collected by research ships. They are also an excellent complement to satellite observations (particularly from the altimetry satellites in the Jason series).

The Argo observations allow oceanic variability to be measured across all oceans, on the seasonal, decadal and climatic scales. They provide data that are essential to constrain

Fig. 1 – **Example of the deployment of an Argo float.** Argo floats are deployed in all oceans, from research vessels, ships of opportunity and sailing boats. © Ifremer. ■

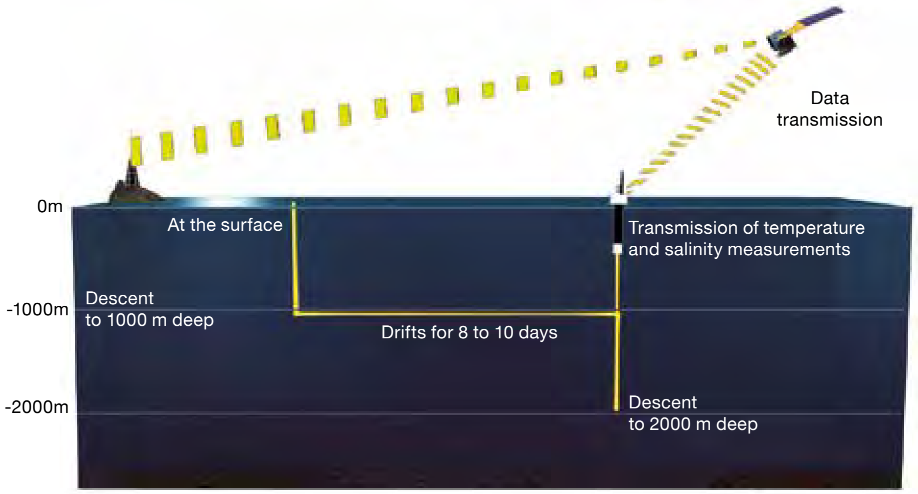

Fig. 2 – **How Argo floats work.** © Ifremer. ■

ocean analysis and forecasting models, to initialize ocean-atmosphere coupled models for seasonal and decadal forecasting, and to validate climate models (cf. III.11). They are also very useful for validating satellite data.

An essential network for global research

France is very active in all aspects of the Argo programme: instrument development (Provor and Arvor floats), contribution to the array by deploying 70 to 80 floats per year (around 10% of the international effort), global data centre (with the Coriolis centre in Brest), measurement validation, research (ocean circulation, climate, biogeochemistry) and operational oceanography (Mercator Océan and the Copernicus Marine Service). France also coordinates the European research infrastructure Euro-Argo ERIC: the European component of Argo.

In the space of a few years, Argo has become the most important source of data for researchers studying the ocean and its influence on the climate. In particular, the measurements from the network have helped to significantly improve estimates of heat storage by the oceans. This is a decisive factor for estimating the extent of global warming and the Earth's energy balance, and improving our understanding of the underlying mechanisms of mean sea level rise (cf. II.15). Argo data have also allowed monitoring of the deep convection events that influence thermohaline circulation and meridional heat fluxes. The comparison of Argo observations with past data has shown long-term variations in the salinity of the oceans, connected with the intensification of the water cycle. The use of Argo measurements, combined with measurements from altimeter satellites, has also allowed outstanding advances in the representation of the ocean required for ocean forecasting and seasonal forecasting.

Argo's first challenge is to maintain the current array over the next 10 to 20 years. Research on climate change urgently needs very high-quality, long-term, global observations. The second challenge is to develop the array, to answer new scientific questions and expand its range of applications: covering the polar zones and the marginal seas, extension to greater depths (from 4000 to 6000 metres), and the addition of biogeochemical sensors (oxygen, chlorophyll a, pH, particulate organic carbon, nitrate). Beyond the pilot projects (such as the NAOS project in France), the major challenge today is to establish the two main extensions of the Argo global programme: the observation of the deep sea (Deep Argo) and the development of a network of floats with biogeochemical sensors (Biogeochemical Argo). These extensions should improve our understanding of the role of the deep ocean in the Earth's energy balance, the deoxygenation and acidification of the ocean and their impacts on ecosystems, the carbon cycle, and the interactions between physics and biogeochemistry.

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5. Sea bed and water column observatories

Mathilde Cannat

More than two thirds of the Earth is below sea level and the oceans are a major instrument in the dynamics of our planet. They are climate regulators, a key reservoir for exchanges between the Earth and the atmosphere, and act as the scales for the global balance of the planet…

Technical challenges

Until recently, the oceans and sea beds were studied only through oceanographic expeditions lasting a few weeks, often restricted by seasonal climate windows. The data were therefore collected over short periods, in very precise zones, and were not renewed until the next campaign – generally several years afterwards. This approach, which does not allow us to examine the temporal variability of phenomena, prevailed until the mid-1990s, because oceanography (from geophysics to biology) was in a phase of discovery at this time. So little was known about the oceans that the priority for researchers was exploration. On top of this, scientists faced several technical difficulties: data transmission from instruments deployed on the seabed or in the water column, supplying energy to these instruments over periods of at least several months, and designing sensors that could provide the necessary data. There is still much to be done on this last point, as many critical parameters (chemical or biological) are still only measurable in laboratories using samples. These cannot be transmitted by fibre optic or satellite technology. However, from the early 2000s, due to advances in digital data transmission methods and energy supply to sensors, two types of marine observatory systems could be constructed.

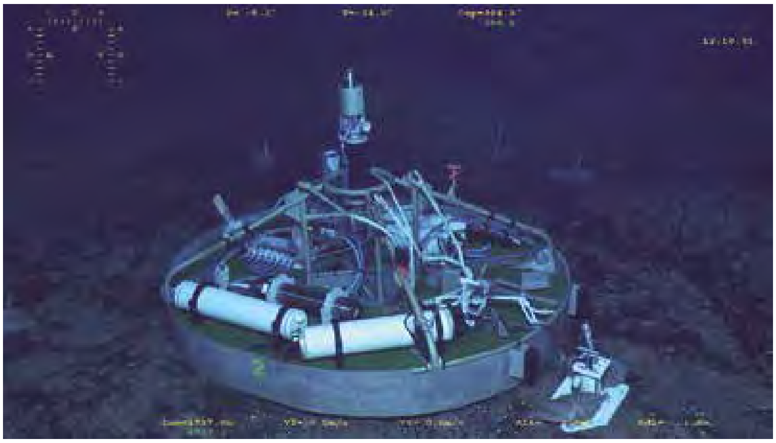

Fig. 1 – **The seismic and geodetic measurement module of the EMSO-Azores Observatory, currently in place on the axis of the Mid-Atlantic Ridge.** The chambers contain the electronics and batteries; the instrument on the ground is a seismometer. On top of the module is an acoustic head, which transmits the data to a buoy. © ROV VICTOR Ifremer / CNRS, 2016. ■

Observation systems

The first type of system is currently used to study the water column. It consists of instruments installed on mobile platforms ('Lagrangian platforms') which move mostly with marine currents. For example, the ARGO system currently has 4000 floating platforms distributed in all the oceans. These can transmit the salinity and temperature of the sea water by satellite.

The second system is more like an observatory. It consists of instruments installed at a fixed point (Eulerian observatories), on the seabed or in the water column. These are supplied with energy by batteries or electrical transmission cables, and send their data by acoustic signal, satellite, or optical fibre if the observatory is cabled. In the deep ocean, such systems currently exist along the coasts

Fig. 2 – **Diagram of the EMSO-Azores system, showing some of the instrument modules, the surface buoy, and the data reception site (on the Ifremer campus in Plouzané, France).** Source: Ifremer. ■

of Japan, where cabled instruments complete the terrestrial seismic monitoring network; along the west coast of the United States and Canada (the NEPTUNE network); and around the perimeter of Europe (the EMSO network, or European Multidisciplinary Seafloor and water column Observatory network).

For the most part, these fixed-point observatories contain many instruments, and serve several disciplines. This can be for practicality reasons, in order to share maintenance expeditions, which are heavy operations that mobilize an oceanographic ship and a submersible each year, or it can be for scientific coherence. These data reveal the variation over time of each parameter measured, as well as the relationships between parameters that appear independent at first glance. They thus encourage new exchanges and synergies between marine science disciplines. For example, the EMSO-Azores observatory, located at a depth of 1700 m on the Mid-Atlantic Ridge (where the African and North American plates are moving apart at a rate of 2.4 cm per year), consists of over 15 different types of instruments. These are dedicated to studying the seismicity and volcanism of this tectonic plate boundary in the zone (Fig. 1), monitoring the temperature and composition of the very hot hydrothermal fluids that escape from the highly fractured rocks (cf. II.19), and studying the fauna and microfauna of these hydrothermal vents, as well as the characteristics of the ocean above (temperature, salinity, current). Certain instruments store their data internally and are brought up for reading every year, but several send their data to land every six hours by acoustic transmission *via* a buoy, then by satellite to the EMSO-France server (Fig. 2). This light and inexpensive system is suited to observatories far from the coasts, and those from which the data does not need to be received in real time, because the objective is not to warn of a threat to populations (for example an earthquake or a tsunami). When the aim is to warn of such a risk, as in Japan, the much more expensive cabled solution must be used.

Access to observatory data

Whatever the system, observatories generate digital data flows, which are accessible in real time over the internet. Formatting, archiving and referencing these data is a technical challenge. Another challenge is gaining the interest of other potential users outside the research world, for example the weather services and marine resource management agencies, but also schools (for educational projects) and individuals who can become actors in participatory science.

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6. *Tara* Oceans : from ocean odyssey to systematic study

Lucie Bittner and Chris Bowler

In the best tradition of the great expeditions of the 19th century, from September 2009 to November 2013 the schooner *Tara* sailed the world, undertaking multidisciplinary, ground-breaking research into the ocean ecosystem. With the most advanced technologies on board, the aim was to collect a diversity of plankton community forms and genomes, as well as gathering the environmental parameters associated with the collection zones. Samples were taken from more than 210 stations in the Arctic and Antarctic and in temperate and equatorial regions, at the surface and at depths of up to 1,000 m (Fig. 1). This was a unique expedition in two features: firstly, the implementation of a novel, standardised protocol leading to the collection of biological (genomic and morphological) data for all plankton lineages, with samples being taken from single-celled eukaryotic protists (diatoms, coccolithophores and forams), multi-celled eukaryotes (copepods and jellyfish), bacteria, archaea and viruses. Secondly, the *in situ* collection of a wealth of oceanographic data for each station, with the use of special sensors, established a sizeable set of metadata encompassing temperature, salinity, nutrient and chlorophyll concentration, as well as derived measurements, such as estimated primary production in the euphotic layer and carbon export to mesopelagic zones.

Fig. 1 – **Sampling itinerary (shown as a blue line) of the schooner *Tara* (*Tara* Oceans and *Tara* Arctic campaigns, 2009-2013).** The 210 stations where samples were taken are shown as red dots. Source: Pesant *et al.*, 2015. © N. LE BESCOT. ■

Large volumes of data and an holistic approach

The scientists on board successfully concluded the task of comprehensive collection (Fig. 2) with guidance from the onshore scientists at the research laboratories directly involved in the expeditions, with whom there was daily communication. Standardised protocols, robust logistics and crew flexibility in response to the vicissitudes of the ocean were key to the project's success and enabled the collection of more than 40,000 samples, along with their contextual data. Once collected, these samples were transported, stored and preserved, and used to produce new and diverse types of standardised data, providing a body of knowledge at planetary scale. The data produced by the distinctive high-throughput, multiscale strategy of the *Tara* Oceans project, addressing biological, physical and geographical facets, thus supplements the oceanic biodiversity surveys of prior expeditions and long-term observation sites. A multidisciplinary team was formed in response to the challenge presented by this ground-breaking collection and its exploitation, enlisting scientists from a variety of backgrounds (oceanography, bioinformatics, biology and physics). This alliance maximises the interactions between different fields of research and their respective specialists, to encourage advances that could not be achieved in isolation within the confines of the laboratory.

Fig. 2 – **In the thick of the action on the rear deck of the schooner *Tara*.** The chief scientist (here, Eric Karsenti) takes samples from the rosette. © D. SAUVEUR / Fondation *Tara* Expéditions ■

A burgeoning revolution in our understanding of the ocean system

Less than two years after the schooner's return, analysis of the first 70 stations had generated 7.2 terabases of environmental DNA sequences and enabled the development of the largest catalogue of ocean-dwelling organisms and marine microbial functions ever seen. The research undertaken by the alliance is exploring the diversity and structure of plankton ecosystems, as well as their relationship to biogeochemical cycles. Five articles published in Science in 2015 and three articles published in Nature in 2016 describe the main initial findings. The majority – 80% – of the 40 million microbe and virus genes detected (four times as many as in the human microbiome) are currently unknown. As shown by prior studies, microbial community structure is influenced primarily by temperature. The large numbers of samples mean that new statistical methods of analysis can be used for quantitative investigation of the plankton interactome, which has shown that biotic interactions (mutualism, parasitism, competition and predation) are even more influential than abiotic factors in terms of community structure. Two major findings – this prevalence of symbiosis *sensu lato* and the substantial presence of mixotrophic lineages – will tend to point the way forward for our near-term view of trophic networks in the marine environment. A separate study, using co-occurrence methods, has embarked on the partitioning of the massive genomic dataset, uncovering the communities of organisms and genes involved in carbon export in oligotrophic zones. This approach is generating landmark results and detecting key sequences which are ideal candidates for the development of biomarkers to monitor the biological carbon pump. The meta-omic data are thus providing new perspectives and solutions for the study of biotic and abiotic processes and for the major biogeochemical cycles throughout the global ocean.

Future destinations

The studies by the *Tara* Oceans alliance illustrate how the analysis of the structure and dynamics of the infinitesimal can be considered in a planetary context (with ocean currents, temperature gradients and nutrient cycles), and how such patterns can be leveraged to infer the global processes at work. Thanks to the large amount of data and the multidisciplinary approach introduced by the project, it is just a short step from molecular oceanography to sound predictive models of the ocean ecosystem. In combination with dedicated modelling, future studies will further our understanding of the interaction, adaptation, and evolution of life in the ocean in the context of ongoing climate change.

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7. The French oceanographic fleet

François Jacq

A bit of history

The 16th century saw the rise of organized expeditions (Spanish and Portuguese), whose vocation was the conquest of wealth, but also the desire to discover new spaces. The first scientific expeditions, such as those of James Cook or Jean-Francois de La Perouse, did not begin until the 18th century. The development of science in Europe was accompanied by the institutionalization of new forms of knowledge acquisition, during an increasing number of scientific, terrestrial and marine campaigns, such as those of Charles Darwin in the Pacific.

The end of the 19th century undoubtedly marks the starting point of modern oceanography, notably the explorations of Albert of Monaco, devoted to the discovery of the oceans, a mixture of individual initiative, patronage, and public action. The time of the fleets had not yet arrived, but that of individual ships had. On the other hand, the foundations of subsequent practices were being laid down: dedicated means of exploration, the first forms of international cooperation, the gathering of scientists from different horizons. That time also saw the beginning of the exploration of extreme environments, with the first polar expeditions. Finally, the Second World War marked a shift to new way of practicing science, whether in the means deployed, the technological breakthroughs and the work they enabled, or in the organization of science, in an 'American model' combining science, technology and the role of the State.

After World War II, large-scale specialized organizations in charge of environmental exploration (National Center for the Exploitation of the Oceans in 1967) were created and, in close collaboration, a number of different means of exploration were developed, ships, engines, and sensors that progressively integrated technological advances. Scientific communities were organized in such a way to enable analysis of all the compartments of the oceans: from the coast to the deep sea, from geology to life, from ocean circulation to interactions with the atmosphere.

Fig. 1 – **French ship *Pourquoi Pas?* A 100-meter long oceanographic vessel.** © M. GOUILLOU / Ifremer. ■

The construction of ships designed specifically for scientific expeditions, capable of deploying exploration tools, is indispensable for the investigation of the least known part of our planet. Thanks to this fleet, scientists are discovering new forms of life in the abyss, where the fauna survive in the absence of light, as well as extraordinary biodiversity. Scientists also study the currents and the properties of water bodies, and contribute significantly to climate studies.

The ambition of expanding knowledge is coupled with the desire by states to establish their geopolitical position, in which an ocean is also perceived as a way to establish their power and an exclusive economic zone.

The french fleet

To this end, France acquired an internationally recognized infrastructure: four deep-sea vessels (Marion Dufresne II, Pourquoi Pas?, L'Atalante and Thalassa); seven coastal vessels, two of which are deployed overseas (Thetys II, Côtes de la Manche, L'Europe, Thalia, Haliotis, Alis and Antea); as well as station vessels, which remain in the coastal zone (Fig. 1). The French fleet, which is present in all the oceans and seas of the world, is used to conduct research in numerous scientific fields: marine geosciences, physical and biological oceanography, biogeochemistry, paleo-oceanography and marine biodiversity. Different observation and sampling technologies and strategies are used: a range of submarine machines (manned or not) to explore the seabed down to a depth of 6,000 m, seismic measurement tools (Fig. 2), coring for marine sub-soil studies, water column sampling, en-route measurements (meteorology, currents...). The French fleet is original in its varied purposes: research, with campaigns selected after rigorous evaluation, providing support for State measures (*e.g.* knowledge of fish resources and preservation of ecosystems) and cooperating with different industries (*e.g.* geosciences and for the identification of mineral or fossil resources).

Fig. 2 – **Launch of the CTD rosette bathymetric sounder from the oceanographic vessel L'Atalante.** © S. LESBATS / Ifremer. ■

A changing fleet

Can satellites that observe the globe, or fixed or drift array networks (ARGO) replace the fleet? Of course, the progress they represent has been shaking the foundations of our approaches for the last 20 years, but in fact, they complement campaigns on ships, which alone enable scientists to approach physical or biological reality that closely. Fleets are now more essential than ever. Although each state tends to want to have its own tool, sharing will occur in "boat time", involving exchanges, and mutual invitations. Like any other tool, fleets undergo transformations, allowing shore crews to start making observations at sea, in real time.

The ever-changing oceanographic fleet is thus indispensable for French research. It is the result of constant interaction between scientific needs, technological progress and state policies.

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8. Submersibles for deep sea exploration

Javier Escartín and Catherine Mével

The deep sea is a hostile environment, with thousands of metres of water above the seafloor. Deprived of light, it long belonged to the realm of mystery and fantasy. Even today, as space exploration regularly reveals secrets of our galaxy and beyond, exploration of the deep sea remains a technological challenge. It is thanks to the development of underwater vehicles and technology that scientists can now directly observe the seabed, take samples and perform measurements *in situ*. Deep sea exploration truly began in the 1950s, with the first bathyscaphes and Auguste Piccard, one of the deep sea exploration pioneers. In 1960, his son Jacques descended to a depth of 10,960 m in the Trieste bathyscaphe, in the Mariana Trench. Since then, scientific needs, but also military and industrial ones, have driven the development of a whole range of increasingly advanced tools, and led to huge progress in vehicle positioning, performance, and instrumentation.

Manned submersibles

In 1964, the US Navy and the Woods Hole Oceanographic Institution (WHOI) launched the submarine Alvin, which could reach a depth of 2400 m. In 1969 (the year of the Moon landing), the CNEXO (French National Centre for the Exploitation of the Oceans) launched the Cyana, a diving saucer which could descend to 3000 m deep. These manned submersibles consisted of a titanium sphere, which could withstand the elevated pressures found at great depths, and that were equipped with portholes for observation. These submersibles could carry a crew of three (pilots and scientists), and were equipped with mechanical arms to take samples. 1973 and 1974 saw the first major scientific operation: Project FAMOUS (French-American Mid-Ocean Ridge Underwater Survey). For the first time, the submersibles Cyana and Alvin, as well as the bathyscaphe Archimède, explored the Mid-Atlantic Ridge axis and its extended lava fields. In 1977, Alvin discovered the first hydrothermal vent along the Galapagos Rise. This launched a new field of scientific investigation, connecting geology and ecosystems. Since then, new generations of manned submersibles have been developed. In 1984, IFREMER (the French Research Institute for Exploitation of the Sea) launched the Nautile, which could descend to 6000 m, giving it access to 97% of the seabed. Others followed, such as the Soviet MIRS (–6000 m), the Japanese Shinkai 2000 and 6500, and finally the Chinese Jiaolong (–7000 m). Meanwhile, Alvin's diving capacities were improved also to >6000 m. However, there are still very few manned submersibles able to descend past 2000 m despite all the technical advances.

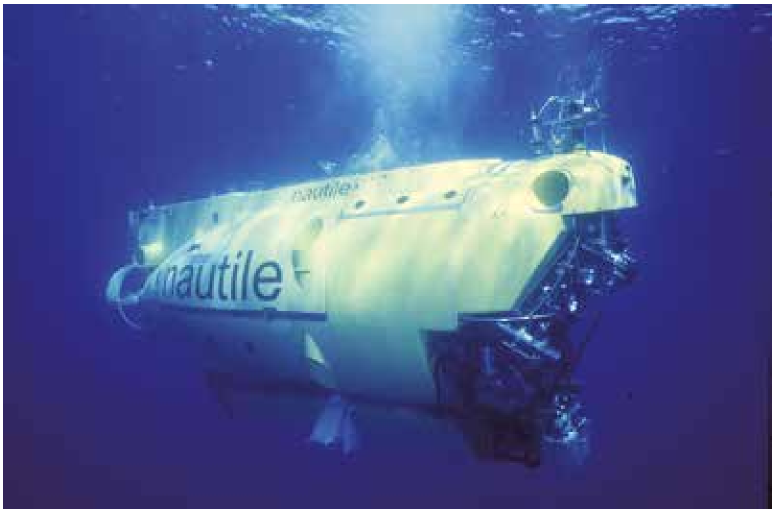

Fig. 1 – **The *Nautile*, a manned Ifremer submersible, designed for observation and intervention at depths of up to 6000 m. © Ifremer / É. LACOUPELLE. ■**

Submersibles are also used by civil society. For example, in 2003, the Nautile intervened to observe the state of the shipwrecked Prestige, an oil tanker which sank in late 2002 off the Spanish coast, causing an enormous oil spill. The Nautile operations managed to stop the leaks.

Fig. 2 – **The AUV Aster X (IFREMER), an autonomous vehicle weighing around 800 kg, which can descend to depths of up to 3000 m.** © Ifremer / O. DUGORNAY. ■

Devices towed near to the seabed

Using manned submersibles is labour-intensive and requires a very high-level technical environment, which is not always available on oceanographic ships. For this reason, devices were developed in parallel to be towed near the seabed. This provides an easy way of collecting measurements and observations. Connected to the ship by a cable, they were initially rather rudimentary and dedicated to photographing the seabed. However, these systems were gradually improved, especially thanks to the use of electrical transmission cables, which allow communication with the ship, and therefore provide control over data acquisition. The range of sensors has also diversified greatly. Scientists frequently use video systems, sonar to measure seabed reflectivity and therefore provide information on its geological nature, magnetometers, physical and chemical sensors to detect anomalies in the water column…

Remotely operated underwater vehicles

The development of remotely operated underwater vehicles (ROVs) was a huge step forward. These robots transmit images from the seabed in real time, and are equipped with mechanical arms which can be manipulated from the ship. They were developed for commercial purposes from the end of the 1970s, to be used on oil facilities or undersea cables, but they could only reach very limited depths. Scientific demand led to the development of deep-sea ROVs. In 1988, WHOI launched Jason, followed by IFREMER's VICTOR in 1992. Both were capable of diving to 6000 m. There are now many of these deep-sea ROVs, which are regularly used on scientific research expeditions. They are connected to the ship by an electrical transmission cable, which transmits both energy and data. Controlled from the ship, the ROV sends images in real time. These are displayed on screens and used to guide the dive, sampling and use of scientific instruments and sensors. ROVs are less manoeuvrable than manned submarines, because of the cable connecting them to the ship, but there is no limit on the time they can spend on the seabed.

Autonomous vehicles

With the development of robotics from the 1990s, truly autonomous vehicles could be put to work. The era of scientific deep-sea AUVs (Autonomous Underwater Vehicles) began with the ABE, an AUV from WHOI. The last twenty years have seen a boom in the development of these vehicles, with all sorts of scientific, military or industrial applications. Before they are launched, they are programmed to conduct a survey of a selected zone by recording data. Depending on the sensors installed, they can carry out high-resolution bathymetric surveys, measure the physical and chemical parameters of the water column, locate shoals of fish… For the moment, their autonomy and intervention capacities are limited compared to those of ROVs, but given their ease-of-use and the speed of technological progress, their future is particularly promising.

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9. Measuring the relief of the ocean floor

Javier Escartín

At the start of the 20th century, the topography of the seabed was completely unknown. To measure depths, the technique of a weighted line was still used until the 19th century. This provided only very fragmentary knowledge. It was during the first true oceanographic expedition, on the British ship HMS Challenger (1872-1976), that a depth of 8200 m was measured in the Mariana Trench. However, only with the technological advances of the last century was the relief of the ocean floor finally revealed to us.

The first echo sounder

The first step was taken with the invention of the echo sounder in the early 20th century. The echo sounder emits an acoustic signal towards the seabed and measures the time taken for the echo to return. Knowing the propagation speed for acoustic waves in water (around 1500 m/s), we can calculate the depth. The first systematic bathymetric measurements using an echo sounder were taken aboard a German oceanographic ship, the Meteor, which criss-crossed the Atlantic many times in the 1920s. It showed the presence of a massive mountainous relief in the middle of this ocean, now recognized as the Mid-Atlantic Ridge.

Fig. 1 – **North Atlantic undersea relief, from the 1977 physiographical map by Marie Tharp and Bruce Heezen.** This map, based on bathymetric profiles, shows the mid-ocean ridge split by transform faults, and numerous volcanic seamounts. ■

During the Second World War, acoustic techniques were improved by the military services, and thousands of kilometres of bathymetric surveys were collected. In the 1950s, Marie Tharp and Bruce Heezen of the Lamont Doherty Geological Observatory (USA) compiled the available bathymetric data. Combining data, intuition and interpretation, they put together a physiographical map of the ocean floor. The first map of the North Atlantic, published in 1959, revealed the continuity of the Mid-Atlantic Ridge and its offsetting by large transform faults. The world map, published in the 1960s, was the first overview of undersea relief, and showed the distribution of oceanic ridges and trenches. It played a major role in the development of the theory of plate tectonics and in our understanding of how our planet works.

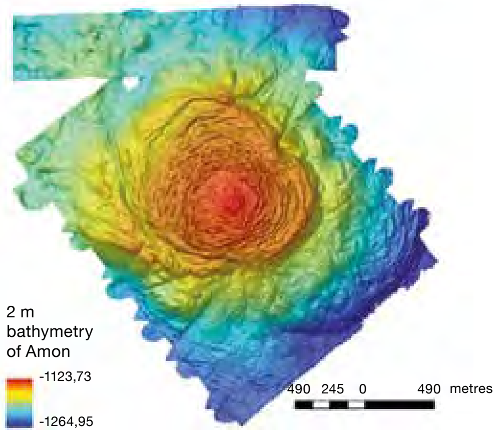

Fig. 2 – **High-resolution bathymetric maps of the Amon mud volcano in the deep Nile delta, in the Mediterranean.** This map cames from the BIONIL expedition (Meteor oceanograpic ship) with IFREMER's Aster X AUV. According to S. DUPRÉ *et al.*, 2009. ■

Multi-beam sounders

The 1960s saw huge progress, with the development of multi-beam echo sounders by the US Navy, to support submarine activities. The first commercial multi-beam sounder, the SEABEAM, launched in 1977, allowed a survey of the sea floor from a ship, with 16 acoustic beams across a 45° arc, giving an acoustic swath equal to 3/4 of the depth. It was first used for scientific purposes on the Jean Charcot oceanographic ship in 1978. This allowed a zone of the Mid-Atlantic Ridge to be mapped in detail, opening the door to more precise studies of seabed morphology. More recent multi-beam systems are much more effective. The sweep angle has increased from 45° to 140°, the size of the acoustic swath increasing from less than 1 to 5.5 times the water depth, and the number of measurement points from 16 to several hundred. Yet despite these technological advances, mapping the ocean floor using echo sounders requires significant survey time. Currently, less than 10% of the seabed has been mapped at resolutions of 50 to 100 m. Mapping the remaining 90% with the current systems would take over 250 years of non-stop surveys by one ship! At present, we have more precise knowledge about the surface morphology of planets like Mars or Venus than we do about the Earth's surface morphology.

Satellite bathymetry

Putting satellites with altimetric radars in orbit has allowed a second revolution in the global knowledge of undersea relief. For reasons of mass variation, undersea high relief generates bumps, whereas trenches generate depressions in the surface of the sea. By combining bathymetric measurements taken from ships, density models of the oceanic substratum and sea level measurements from satellites, in the 1990s David Sandwell's team from the Scripps Institution of Oceanography (USA) drew up predictive bathymetric world maps, with kilometric precision. These maps, which are regularly improved, are invaluable tools for the scientific community, because they provide a global picture of the geometry of ridges, seamount distribution, and large oceanic faults and trenches. They allow zones of interest to be targeted, so that they can later be studied in detail from ships. Moreover, they are used well beyond the scientific community, for all sorts of purposes.

High-resolution bathymetry

Neither the maps derived from satellite measurements, which remain predictive, nor the bathymetric data acquired using boats with a resolution of around 100-50 m, can provide high-resolution images like those obtained on land. It was not until around thirty years ago that the development of underwater vehicles with multi-beam sounders allowed us to get close to the ocean floor and obtain very high resolution data (around 10 cm to 1 m resolution). To conduct these surveys, scientists now use drone-like AUVs (Autonomous Underwater Vehicles), that are programmed to map while flying close to the seafloor. However, because of the complexity of submarine operations and the slowness of the vehicles, the surface explored during a dive remains very small. These bathymetric surveys are therefore limited to use in highly detailed studies, and on very precise targets.

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10. Paleoceanography

Elsa Cortijo and Laurent Bopp

In situ measurements (cf. III.2) and satellite observations (cf. III.3) allow us to describe the physical, biogeochemical and biological workings of the ocean today. They also give us a glimpse of the past. For example, by using ocean temperature and salinity measurements taken near-systematically during the second half of the 20th century, scientists can build up a picture of the state of the ocean over the last 70 years. However, these reconstructions become less precise the further back we look, because historical data becomes scarcer: the first oceanographic expedition (the Challenger expedition) was not until 1872-1876.

However, knowledge of the past variations in the ocean's temperature, its circulation and the conditions of life within it is essential to our understanding of how this complex system works. Paleoceanography is the study of the history of the ocean in a pre-tool past, for which researchers have no direct measurements. There are multiple periods of interest: from recent centuries, to the last tens or hundreds of millions of years. To build a picture of past conditions, paleoceanographers employ methods that use indirect indicators (proxies), and they have at their disposal an amazing archive: marine sediments.

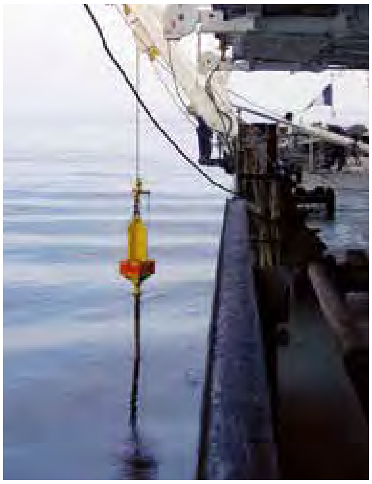

Fig. 1 – **A 'Kullenberg' corer being used on the oceanographic ship *Marion-Dufresne*.** © E. CORTIJO / IPEV. ■

From sedimentology to paleoceanography

Marine sediments are primarily made up of biological or lithogenic particles that fall to the seabed (cf. II.22). These deposits build up over very long periods, thus locking away information on oceanic conditions from the distant to the recent past.

From the 19th century onwards, scientists began examining the nature of these marine sediments, taking samples from the sediment surface. It was only from the 1950s, with the development of 'Kullenberg' type corers (Fig. 1), that oceanographic ships were able to core several metres or tens of metres down, and sample sediment archives dating back several hundreds of thousands of years (or even millions of years). This was the birth of paleoceanography.

In 1955, Cesare Emiliani, an American micropaleontologist, became the first person to apply the fundamental works of Harold Urey (1947) to foraminifera. Urey proposed connecting the ratio of oxygen-16 and oxygen-18 isotopes to the precipitation temperature of carbonates. In the marine sediment archives, Emiliani identified water temperature variations that followed the glacial-interglacial cycles proposed by the mathematician Milankovitch almost 30 years before. Parallel to the development of isotopic geochemistry, other researchers, particularly Imbrie and Kipp (1971), study foraminiferal fauna. Using multilinear regressions between the different species and the summer surface water temperatures (known as 'transfer functions'), they ascertain the surface water temperatures over the last several thousand years.

Reconstructing ocean surface temperatures

The reconstruction of past ocean temperatures is one of the primary objectives of paleoceanography. Paleoceanographers today use several different 'paleothermometers'. The most common is based on analysing oxygen isotope ratios in the calcium carbonate tests of foraminifera. When the water is warmer, the animal's skeleton is rich in oxygen-16: the lightest isotope. The opposite applies when the water is colder. However, there is an additional layer of complexity: the isotopic composition of seawater also varies with the quantities of water stored on the continents, as shown by Nick Shackleton in 1967. The formation of large polar ice caps tends to deprive the ocean of oxygen-16, which is mostly stored in polar ice. Thus, the variations in the isotope ratio of foraminifera 'record' the volume of the continental ice sheets and a local temperature: that of the water in which the animal grew. Planktonic foraminifera are therefore analysed to reconstruct surface sea water temperatures, and benthic foraminifera to reconstruct temperatures at the bottom of the ocean. Today, other paleothermometers are used in conjunction with the isotopic approach, particularly the ratio of magnesium and calcium in tests on foraminifera, the degree of alkenone unsaturation (alkenones being lipids synthesized by a calcifying phytoplankton), or the relative proportions of other different micro- or nanofossil species, such as coccoliths and diatoms.

These methods have been applied on several timescales, but the most emblematic example is that of the surface temperature estimates for the last glacial period, around 20,000 years ago. As part of the 2006 MARGO international project, almost 700 temperature estimates were gathered and re-evaluated. These data show extreme cooling in the North Atlantic (almost 10° cooler than today), but much less significant cooling in the tropics (less than 2°C cooler). These indications are essential when it comes to estimating how our climatic system and the ocean react to variations in climate forcings.

Fig. 2 – **Extraction of a core using a manual pneumatic pressure drilling technique (Wheeler Reef, Australia).** © L. MONTAGGIONI / CNRS Photo library. ■

For surface water temperature reconstructions, each of these methods taken alone presents around a 1 to 2°C margin of error on average. By combining several of these methods, we can reduce errors in temperature reconstructions.

Other characteristics, other archives

Evidently, the reconstruction of temperatures using sediment archives is only part of the research work of paleoceanographers. Other parameters that help us reconstruct a more complete history of the ocean are also revealed by studying minerals or micro-organisms collected in sediment cores (Fig. 2): the salinity and pH of seawater (boron isotopes in calcium carbonate), the intensity of major marine currents (magnetic particle orientation), biological productivity (carbon isotopes of benthic foraminifera)...

Other types of marine archives have also proven to be useful complements, such as corals which secrete a calcium carbonate skeleton (Fig. 2). The isotopic composition of this skeleton can tell us about several parameters of the environment in which the corals lived. However, alongside the sediment archives, this coral archive provides a picture at high temporal resolution, allowing scientists to study the inter-annual temperature variations of climates very different to today's. This information allows us, for example, to reconstruct past El Niño events and analyse how they differed from those seen today.

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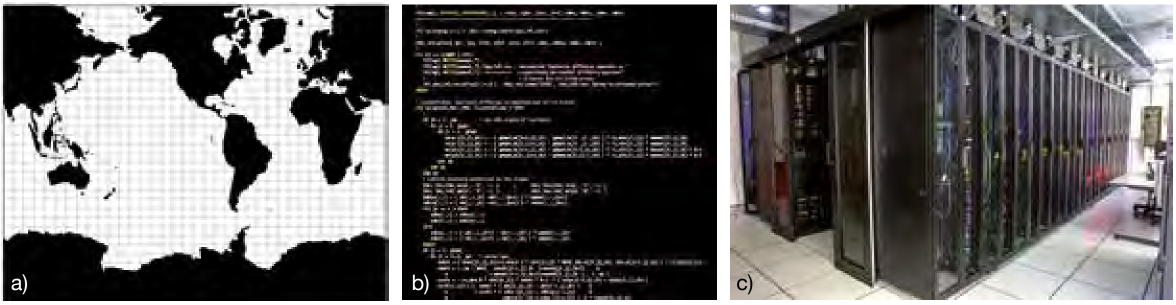
11. Numerical modelling of the ocean

Julie Deshayes and Olivier Aumont

The numerical modelling of the ocean involves simulating observable characteristics of the ocean based on physical, biological and chemical hypotheses about the relationships between these variables. These characteristics can describe water masses and their movements (temperature, salinity, marine currents...), sea ice (expansion, thickness, age...) or the ocean's biogeochemical properties (quantity of dissolved organic and inorganic carbon, pH...). The observa-tions of these characteristics (by satellite, cf. III.3, or by *in situ* measurement, cf. III.2) are indispensable for producing, validating and interpreting the simulations generated by modelling. In return, these simulations are useful for recon-structing the spatio-temporal context of spot observations, and for analysing the role of the different processes at play. Furthermore, because of the ocean's key role in the climate system (cf. I.3), numerical modelling of the ocean is an essential element for reconstructing the past climate, understanding the current climate, and predicting the future climate.

The history of numerical modelling

In the early days of oceanography, geophysical fluid physicists tried to theorize the characteristics and movements of water masses, based on the fundamental principles of mechanics and thermodynamics. These attempts, conducted from the early 20th century, in parallel with the improvement and multiplication of oceanic observations, focused on estab-lishing and then solving the fundamental equations of physical oceanography. The analytical resolution of these equa-tions (by hand) was therefore consistent with the very limited number of observations of the ocean. However, the growing number of observations and the failures of theory to reproduce these observations have revealed the importance of complex phenomena (non-linear processes, factoring in the relief of the seabed, deep stratification), which make the system of equations too complex to solve on paper. Moreover, solving these equations numerically provided a response to the emerging interest in future climate projection. This is how numerical modelling of the ocean began, around the end of the 1970s.



a) Horizontal grid of the NEMO eORCA1 configuration (global ocean at a 1°×1° resolution). Each grey square contains 100 cells of the model. **b) Example of Fortran 90 code from the NEMO model. c) ESPRI IPSL mesocentre at the École Polytechnique.** © École Polytechnique / J. BARANDE. ■

Marine biogeochemistry is very closely connected to ocean dynamics. The development of the first numerical models of the ocean allowed the emergence of numerical modelling of the oceanic carbon cycle in the late 1980s. Before, there were only theoretical models of phytoplankton and of phytoplankton-zooplankton interactions.

In the 1990s, about ten global oceanic models were developed. Using these, it was possible to simulate the general circu-lation of the oceans and, for some of them, the oceanic carbon cycle. These models were distributed freely within user communities, which allowed their usage to spread, and made intercomparison exercises between these different models possible. Then, in the 2000s, a fully integrated vision of the climate system emerged. This led to the appearance of the first models of the Earth system, of which the 'blue-white-green' ocean (dynamics, sea ice and marine biogeochemistry) is a major component. Currently, these models are used for future climate projection exercises, which provide information for IPCC reports.

Principles of modelling

There are three major stages in the construction of oceanic models. Firstly, it is necessary to define the system to be represented. This could be the global ocean, a region, or a specific structure such as an eddy. During this stage, the theoretical (mathematical) formalism is chosen. For ocean dynamics, the researchers use equations from geophysical fluid dynamics. For marine biogeochemistry, the modelling is based on physical equations for describing transport of chemical species and plankton, and on empirical formulations for representing biological processes. The second stage is the spatial and temporal discretization of the selected equation systems. For this, a grid of the represented domain must be defined. Decisions must be made on aspects like the spatial resolution and the cell geometry. Processes that are impossi-ble to represent explicitly, either because they are characterized by a spatial and temporal scale which is finer than the chosen resolution, or because they are too complex to describe precisely, must be parameterized often using empirical relationships. Finally, the boundary conditions must be prescribed, including, for example, the oceanic conditions at the boundaries of the domain and the interactions with the atmosphere. The third and final stage is the translation of the model into computer code, and its execution on computers. During this stage, questions regarding performance, repro-ducibility and results archiving are posed. Since oceanic models are often very expensive in terms of computer calcula-tion, the simulations are primarily done on massively parallel supercalculators with thousands of processors, located in dedicated regional or national calculation centres (Fig.).

Taking into account all the possible choices at each stage in the creation of an oceanic model, in theory, the number of possible models is infinite. In practice, the international oceanographic community pools its development efforts. Cur-rently, around twenty models of ocean dynamics, sea ice, and/or marine biogeochemistry are used. These models are developed by researchers and engineers, to meet the needs of one or more applications: academic research on oceanic processes, climate projections or operational oceanography (cf. III.12). When comparing the simulations produced by these models to corresponding observations of the ocean, it is necessary to take into account the uncertainty about both the observations and the models. Although the models are primarily based on deterministic equations, the simulated variables contain a significant portion of random signals. The finer the spatial resolution of the grid, the greater this portion. The random component of the simulations can be evaluated and eliminated by the production of an ensemble of simulations, very close to each other, similar to the sets of predictions used for meteorological forecasting. However, this requires massive computer calculation resources.

In conclusion, there is no universal model of the blue-white-green ocean which meets all the needs of scientific and non-scientific users. The numerical modelling of the ocean is an oceanographic discipline which interacts strongly with many other scientific disciplines, including observational oceanography, marine biology, applied mathematics and computing.

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12. Operational oceanography

Pierre Bahurel

Operational oceanography answers the question ‘what is the ocean like?’ It tells us what the ocean is like, what it was like, and what it will be like, just as meteorology informs us about the atmosphere. Operational oceanography transforms our knowledge into information that is directly usable by those who need it. Indissociable from the study of the oceans, it takes the most advanced form that the sciences and techniques of its time allow. In the past, this was a map drawn to show the estimated position of the Gulf stream. Today, it is real-time digital reports describing the complex three-dimensional state of the ocean and its variations.

One science, multiple technologies

Operational oceanography took on its modern dimension at the turn of the century. This was when Earth observation satellites made reliable, real-time measurement of oceanic surface variables possible (with the satellite altimeters Topex/Poseidon and Jason, which measure the surface topography of the sea, cf. III.4). It was also when marine measurement networks integrated autonomous instruments that could transmit their depth measurements in a very short space of time (the ARGO network made up of a fleet of 3000 autonomous profilers surveying the oceans, from the surface to a depth of 2000 m, cf. III.3), and when high-capacity IT infrastructures became accessible to oceanographic engineers and researchers. However, these technological breakthroughs still needed to find favourable ground: this came when the research community reached a high level of maturity in terms of data processing techniques, modelling and simulation, with influential support initiatives at organizational level. Thus, in barely twenty years, operational oceanography has made the ocean accessible to all.

The ocean in all its states

Oceanographers can now operationally reproduce, analyse and forecast the physical and biogeochemical state of the ocean, at any point on the planet and at any depth. For example, they can determine the speed and direction of oceanic currents, the temperature and salinity, the sea level, ice thickness and drift, the dissolved oxygen level, and the chlorophyll and nutrient concentration. In a single effort, anyone can assess the salinity changes in the deep waters of the South Pacific for the coming week, and analyse the ice cover variations in the Arctic over the past ten years. These large operational modelling systems offer a real-time description of the state of the ocean (analysis), generally accompanied by ten-day change forecasts. However, they also describe past developments over several years (re-analyses) to depict medium-term trends. These retrospective analyses offer the advantage of finer data processing,

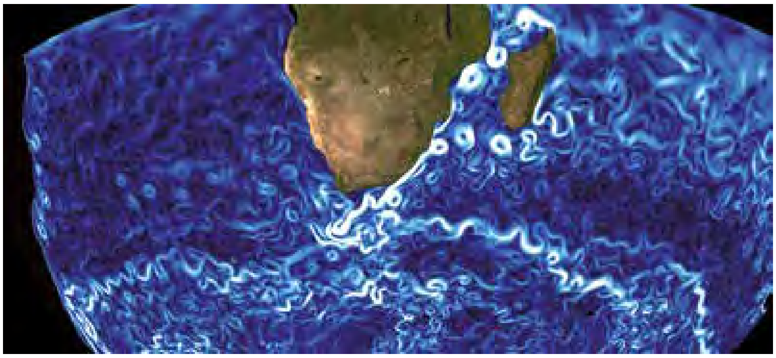

Fig. 1 – **Ocean currents and eddies off South Africa, described by the ocean forecasting system Mercator Ocean, which assimilates spatial observations in real time and on site, to create an ocean model (1/12°, 50 levels) based on the NEMO code.** Source: Mercator Océan. ■

Fig. 2 – **Transoceanic chemical tanker.** Maritime transport is a major field of application for operational oceanography. Public domain. ■

in terms of both observation and modelling/simulation (Fig. 1). They provide a fundamental service, not only because they allow us to assess the normality or abnormality of the present situation, but above all because they help us understand the ocean climate.

Why describe the ocean? Uses and users

The ocean is essential not only for the balance of our planet's climate and that of the coastal environment, but also for the balance of our global economy. The applications of operational oceanography naturally relate to these major climate, ecological and socio-economic issues (Fig. 2). Understanding the state of the currents, for example, is necessary for marine monitoring, combating pollution, and all kinds of operations at sea (shipping and sailing, oceanographic research, safety of goods and people, offshore activities...). Knowing the ocean's temperature, salinity and nutrient concentrations helps us to keep our use of offshore marine resources sustainable, and to protect and manage the marine environment of our coastal waters and shores. Finally, monitoring all of the oceanic variables over time, including sea ice, is useful for experts studying climate change and its impacts. In each of these domains, the uses can take very different forms: rapid collection of information by a non-expert wanting a general overview, or in-depth analysis of terabytes of data by researchers requiring raw material for their own investigations. In fact, research is both an important contributor to and one of the major beneficiaries of operational oceanography, which provides it with the huge data sets and digital simulations that modern oceanography requires today.

A general interest service

Operational oceanography has therefore managed to create a real scientific dynamic, driven by a community of engineers and researchers. It has engaged thousands of users, whose demand in turn feeds constant, innovative research. More recently, it has succeeded in implanting services in the economy, supported by a general-interest ocean analysis and forecasting service. As a result, data on the state of the ocean has been recognized as a public good, which is freely shared by all, with no charge. France has managed to export its operational oceanography approach at European level, thanks to its scientific ambition and international openness, and it is clearly Europe (with its Copernicus programme) that will allow this general interest service to take on its full dimension. The future of this discipline depends on the balance between these three elements: science, usage and economy. Each of them brings its own challenges: the scientific challenges of enriching operational oceanography with a realistic description of life, and of connecting the ocean to other components of the Earth system; the usage challenge of ensuring everyone can access the information contained in the petabytes of data from these large systems; and the economic challenges of definitively integrating this service into our everyday lives, and providing reliable and ongoing access to our knowledge of the ocean.

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13. Sensors and instruments for exploring and observing the ocean

Christian Tamburini, Séverine Martini and Dominique Lefèvre

To explore and observe the ocean over periods of more than a decade (as is necessary to detect change), the development of sensors and/or instruments is a pressing challenge.

Oceanographic sensors

A sensor allows us to record a physical value and transfer it in the form of a quantitative signal. In general, it is coupled with a measurement instrument for acquiring, storing and displaying the signal. The output signal has a unit, an observation window and a precision level. The important properties of an operational sensor are: its sensitivity (capacity to detect small variations), its range of measurement, its response linearity over the whole range measured, and its selectiveness (capacity to return the signal of interest without interferences from other environmental properties). Often neglected, the metrology of the instruments is essential, because only with perfect calibration can the acquired data be validated. There are instruments for physical, chemical, optical and acoustic measurement. Sensors and instruments specifically developed to explore and observe the ocean provide a better understanding of its biogeochemistry, biology and physics: the properties that characterize the dynamics of the oceanic environment.

The most commonly used sensors in oceanography allow the measurement of a range of physical variables (temperature, salinity, density, speed, direction of currents, turbidity). More recently, the development of geochemical sensors has made it possible to measure dissolved oxygen, pH, nutrients and particle load, or even to conduct on-site imaging for the identification of zooplankton. Nevertheless, few sensors or instruments are able to detect organisms or measure biological activity. A few recently developed approaches are: methods combining satellite images of water colour (cf. II.7) and the determination of phytoplanktonic classes; approaches allowing access to high frequency on biological parameters, such as onboard or underwater flow cytometry; and *in situ* measurements of oxygen dynamics.

Deployment platforms

According to the scientific objectives and scales of interest, these sensors and instruments can be deployed on fixed platforms (moored platforms, cabled observatories) or mobile platforms (marine drones).

For fixed platforms, the challenges differ depending on whether the system is cabled (autonomy, transfer and volume of data) or autonomous. Autonomous platforms present major energy and data transmission constraints, especially with the multiplication of measurement systems on the same platform. Cabled observatories provide access to high-frequency, real-time data sets, which can meet operational needs.

Among mobile platforms, bio-loggers (sets of sensors attached to marine animals such as elephant seals, cormorants, turtles or penguins) allow us to describe the behaviour of animals in their environment. Sensors can also be used for applications that were not necessarily envisaged at the outset, by processing and using the data in new ways. For example, acoustic data on elephant seals can be used to evaluate bioenergy values and eco-physiological values (swimming speed, breath count, heart rate) and fishing success (noises associated with ingesting prey), but also to evaluate the state of the sea, using measurements of the ambient noise level and the bio-acoustic landscape (cf. III.15). Only by collecting high-resolution data can we develop and evaluate these new methods, before

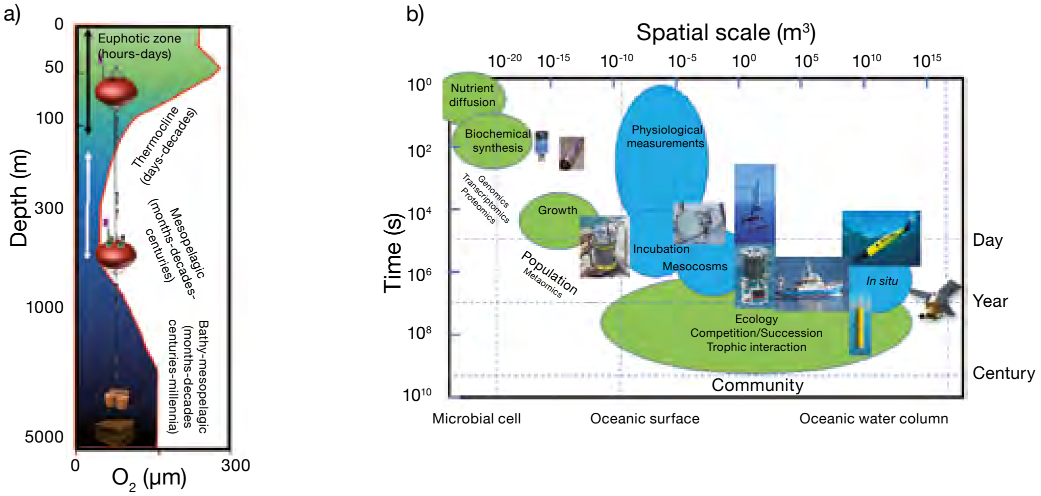

Diagram showing the temporal and spatial scales of physical, biochemical, biological and ecological processes, and the sensor platforms used for observing these phenomena. a) Vertical distribution of oceanic zones and the associated timescales, where moored platforms are the most widely used for carrying sensors in Eulerian observation. b) Spatiotemporal distribution of processes, with an illustration of the sensors and the platforms that carry them. From left to right, the diagram shows: an O_2 sensor, an optical sensor, a submersible cytometer, an on-site incubation system, a marine video profiler (top), a CTD rosette (bottom), an oceanographic ship, an underwater glider (top), an Argo profiler (bottom) and a satellite. © D. LEFÈVRE. According to MOORE *et al.*, 2013. ■

envisaging the best strategy for reducing and compressing data.

Chemical, physical and technical constraints

However, deployment in the marine environment subjects sensors to different chemical constraints (such as corrosion due to salinity) and physical constraints (like pressure at depth). They are also subject to biological constraints, with the rise of microbial biofouling and the increase in benthic species (mussels, phytoplanktonic species at the surface, encrusting species). Finally, a major constraint of their use lies in the data acquisition flow and data transmission. Many recording devices allow high-frequency sampling, or sampling of several variables at the same time, but the possibilities for storing this information and sending it in real time remain limited (Fig.).

The considerable improvement in the performances of industrial products, for competitive budgets, has allowed major progress in the development of new oceanographic sensors and instruments, particularly in terms of transmitting data and managing energy issues. Nevertheless, progress in the communication of data remains limited compared to the advances in acquisition with multi-parametric sensors. On-site processing of the signal, which requires less energy, is a potential way forward. This local processing within the sensor is becoming a priority, due to the limitations of communication channels.

One current trend is to combine several sensors. However, using several sensors increases energy costs. Energy simulations are therefore necessary, as are compromises in terms of information gain versus energy cost and platform lifespan. Lithium cells or batteries are the most commonly used solutions. Performance improvement relies on reduced energy costs, based on a combination of various energy production sources (solar power, marine current power, wind power) and batteries.

Like measurement instruments and platforms, sensors are constantly evolving towards miniaturization, with improved reliability and reproducibility, minimal electricity consumption, and optimized data storage to allow the transmission of useful data for analysis and for monitoring the state of the sensor. In hard-to-access zones, research leans towards smart pre-processing of the signal, to transmit a mathematical function/equation characterizing the signal, rather than raw data. This reduces the flow of data sent.

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14. The ocean: a difficult environment to observe

Christophe Guinet

Observing the ocean is of great importance, so that we can better describe and understand the changes occurring there, and evaluate the influence of the physical processes behind the organization and distribution of marine life. 93% of the excess heat related to the radiation imbalance of our planet is stored in the global ocean (cf. II.10), where it is distributed unevenly. Furthermore, the ocean, which is fluid and perpetually moving in its three-dimensions, has strong spatio-temporal dynamics. Finally, the interactions between physical and biological processes create a heterogeneity that is mostly controlled by physical parameters such as temperature, salinity (density) and light, and driven by horizontal and vertical currents.

Major research efforts are deployed to model these physical processes and predict the global ocean's response to climate change, but they are hindered by a lack of *in situ* measurements, particularly in zones at high latitudes, and for the winter periods.

Observation difficulties

Observation satellites are remarkable tools for studying the oceans and how they work, particularly when it comes to evaluating how the oceanographic landscape shapes primary production. However, satellite observations are restricted to the surface of the oceans. Many tools are used to survey the deeper waters, particularly thanks to oceanographic ships (cf. III.7). However, these tools are expensive, and cannot guarantee access to sea ice zones during the winter months. Over the last two decades, the combination of spatial observations with data from autonomous profilers (ARGO, cf. III.3) has revolutionized the study of the oceans, by allowing us to obtain a near global picture of the physics of the oceans on a medium scale. However, sea ice zones are still inaccessible to satellites, and profilers cannot operate in these conditions. Moreover, these measurement systems do not currently give us access to the physical dimension of the oceans. Today, the recent incorporation of biogeochemical sensors on a small number of profilers provides information on the vertical distribution of phytoplankton.

Fig. 1 – **Young male elephant seal from the Kerguelen Islands, fitted with an oceanographic tag.** © J.-B. PONS. ■

Research assistants

Information on the intermediate trophic levels about which we are least knowledgeable (mesopelagic organisms, zooplankton, gelatinous organisms...) is often collected using echo-sounding or nets. However, the acquisition of these data is very rarely complemented by simultaneous oceanographic measurements. In this context, marine mammals (as well as diving sea birds and sea turtles) are often particularly useful research assistants when it comes to observing the oceans (cf. III.15), especially for studying the influence of the horizontal and vertical distribution of their prey due to oceanographic conditions. Thus, since 2003, elephant seals have been fitted with tags allowing us to locate them and sample oceanographic parameters during their dives (Fig. 1). This species has the

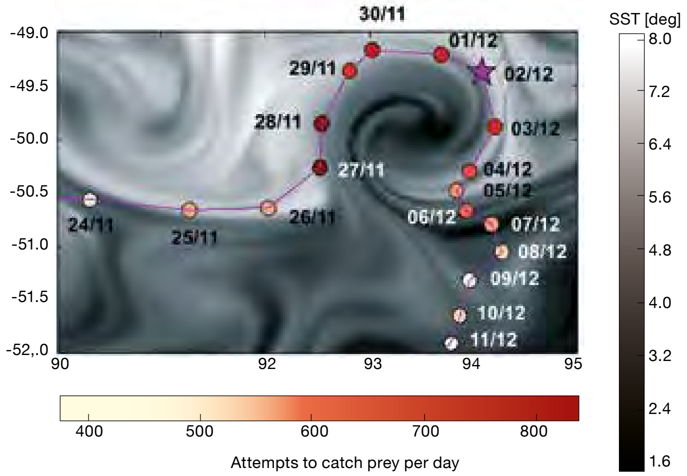

Fig. 2 – **Number of prey capture attempts per day, superimposed over the surface temperature field from AMSR radar observations, for 2 December 2012 and corresponding to the position of the elephant seal marked by the star.** This figure shows that this elephant seal's fishing success practically doubled when it was moving along the external edge of the thermal front associated with the eddy structure revealed by the field. SST = Sea Surface Temperature. ■

particularity of travelling thousands of kilometres, while continually diving (around 60 times a day) to significant depths (500 m on average).

Unlike cetaceans, the seals must return to land twice a year to reproduce and moult, facilitating the deployment and collection of the tags. Initially, only oceanographic parameters (temperature and salinity) then biogeochemical parameters (chlorophyll-a and dissolved oxygen) were sampled. This was done at low resolution (around twenty measurements for each parameter and per profile), three or four times a year. Consequently, elephant seals quickly became an essential component in the observation of the Southern Ocean (a certified 'national observation system'), accounting for 98% of oceanographic data obtained in the sea ice zone. All these data are now freely and internationally distributed *via* the MEOP access portal. However, recent technological developments allow this process to be taken even further, and it is now possible to fit the elephant seals with tags that record temperature, salinity, light, fluorescence, pressure, acceleration, magnetometric data and acoustic data continuously and at high frequency (every second). The data cannot be directly transmitted by satellite, because the volume is too large, but they can be retrieved when the elephant seals return to land. This information not only allows very detailed study of the oceanographic conditions encountered by these animals during their long journey, but it also helps us to identify their attempts to catch prey, as well as the swimming effort expended to catch food. Moreover, acoustic data combined with acceleration and magnetometric information from when the elephant seals surface to breathe allow us to assess the state of the sea: wind strength and direction, wave amplitude and frequency...

Physical and biological interactions

These *in situ* oceanographic and ecological data, combined with data from observation satellites, as well as data on the surface temperature, water colour (cf. II.7), and the level and state of the sea, are a powerful tool for studying the relationships between the physical environment and biological fields. The results show the presence of frontal structures, which may or may not be associated with eddies (Fig. 2) and the presence of phytoplankton on the horizontal and vertical structure of the seals' prey, with direct impacts on their fishing success.

New developments are already being studied, to differentiate between the mesopelagic resources targeted by these predators and those encountered but not consumed. To this end, information from the processing of light will be combined with acoustic reflection measurements taken using an active micro-sounder, which will allow researchers to evaluate the density of the diffusion layers that the elephant seals encounter during their dives. Thus, these animals have become essential tools which complement the other observation methods, for use in studying the relationships between physical oceanography and marine biology, and in the identification of critical marine habitats for protecting these species.

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15. Tracking marine megafauna

David Grémillet

Global changes threaten marine biodiversity and the risk of extinction of larger animals (fish, marine turtles, birds and marine mammals) is particularly high. This crisis, which is mainly due to overfishing (cf. VI.15) and ocean warming (cf. VI.3), seems to be far from being resolved, yet the technological means available to study predators has never been so refined. Recent decades have witnessed the emergence of electronic tools to monitor the movements of marine predators, which have transformed our perception of their spatial ecology.

Electronic Tracking Technologies

The ARGOS satellite data collection system was created in 1978. For the first time, an electronic tracking device emitting on a given frequency could be located anywhere on the planet, with accuracies ranging from a few hundred meters to a few kilometers, at one or more locations each day. The miniaturization of these tags was slow, but in 1990, 100-gram devices attached to the back of wandering albatrosses from the Crozet Islands showed that these birds travel more than 15,000 km across the southern ocean. Many other marine migratory movements were revealed, including the voyages of leatherback sea turtles studied in French Guyana (cf. II.24), which loop the North Atlantic Ocean, linking the Amazonian and Newfoundland coasts with Cape Verde. Currently, 1,800 marine animals are permanently monitored by ARGOS and some tracking devices weigh only 1.5 grams.

The year 1992 saw the development of a method of tracking marine animals based on the recording of light levels. Since day length indicates latitude, and the time of the zenith indicates longitude, a simple light recording makes it possible to geo-locate an animal. Accuracy is less than that of an ARGOS tracking device (a few tens of kilometers), but the measurement of light requires far less energy than emitting a radio signal. Geolocation devices are therefore particularly small (< 1 g), and they can be attached to the rings fixed on the legs of migratory birds. This means scientists can follow the fabulous migration of Arctic terns from the Arctic to the Antarctic, annual trips of more than 70,000 km for a bird weighing only 100 g. Each year, more than 10,000 birds worldwide are equipped with miniaturized light recorders, enabling major advances in migration ecology.

Beginning in the late 1990s, GPS signals were no longer scrambled and their use took on a gigantic dimension, in particular for the monitoring of the marine megafauna. More than 500 studies have been published based on this technology, 50 in 2016 alone. The price of these devices is now low (starting at 40 €), which allows for much more extensive sampling

Fig. 1 – Miniaturization: electronic devices now used to study marine predators are very small, for example this little auk (weighing 150 g) is equipped with a geolocation device weighing less than one gram (blue ring). © D. GRÉMILLET. ■

campaigns than with ARGOS tags. In southern Africa, for instance, a database now contains data on more than 600 seabirds (penguins, gannets, cormorants) tracked by GPS. In addition, GPS can now be coupled to the mobile phone network, enabling data to be downloaded from devices attached to animals without requiring their recapture.

ARGOS tracking devices, geolocators, and GPS, are all very useful techniques for monitoring marine predators that move in the air, or on the surface of the oceans, but they are much less useful for fish, and marine mammals living in the deep. However, the development of a global network of hydro-acoustic tracking stations is currently changing this situation. Each station detects animals within a radius of one kilometer wearing a hydro-acoustic tag, making the network particularly suitable for coastal areas. This is the case of Florida's Atlantic seaboard, which is fully covered by a network of this type, enabling the study of predator-prey relationships, thus touching upon the ecology of communities.

A better knowledge of the hydrosphere

These technological advances have enabled a huge expansion of the spatio-temporal framework for tracking marine megafauna. Some individuals can now be studied throughout their life cycles, across entire ocean basins. Such information has revealed that the hydrosphere, far from being a uniform ecological landscape, is in fact structured by major migratory routes, preferential feeding sites, and wintering or summering areas that some species visit year after year. These studies also show that marine predators are genetically tuned with a superficial knowledge of aquatic landscapes, which they refine over time. By studying dispersal, emigration, immigration and spatial connectivity, electronic tracking technologies thus make it possible to establish functional links between movement ecology and the population dynamics of marine predators.

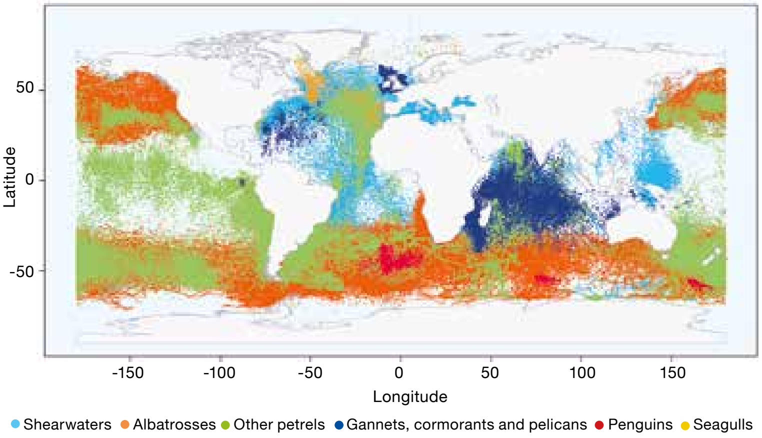

Fig. 2 – **A Global Overview: movements of 113 species of seabirds (694 datasets) studied by 175 research teams.** Source: www.seabirdtracking.org, BirdLife International. ■

Beyond these spatial data, miniaturized devices are now collecting a wealth of information on the behavior and physiological condition of marine predators. In particular, accelerometers make it possible to estimate the animals' energy expenditure, up to the point of knowing the energy cost of each change of direction. Large diving animals, such as elephant seals, can also be equipped with a variety of other sensors that provide information about their physical and biogeochemical environment, transforming them into oceanographic sampling platforms, crossing areas that are basically inaccessible to conventional equipment.

Use of the devices described here requires interactions with wildlife in a very strict ethical and legal framework and scientists are constantly on the lookout for smaller, even lighter devices. The data collected will help ensure better protection of ocean fauna; information on the spatial ecology of these animals is at the basis of the definition of most marine protected areas (cf. VII.11) and of models designed to develop spatialized management scenarios in a changing marine environment.

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16. Exploring nature in the deep ocean

Éric Pante and Sarah Samadi

A brief history

Our understanding of the deep ocean (below a depth of 200 m), an environment covering around 65% of the earth's surface, has developed in line with the advances in technology that have facilitated its exploration. While the very first scientific efforts by Edward Forbes to appraise the deep sea's biological resources led to the assumption that it was an 'azoic' environment, where extreme conditions would prevent life from taking hold below a depth of 600 metres, the great Challenger expedition of 1872-1876 revealed the biodiversity of the deep ocean to the scientific community in all its universal abundance. With the invention of the bathyscaphe and the Alvin submersible it became possible, respectively, to explore the deepest regions of the planet and discover new ecosystems, such as hydrothermal vents and cold seeps. Other less spectacular but equally significant advances in technology and methodology, such as the multi-beam echosounder, remotely operated underwater vehicles (ROV), field monitoring stations and the standardisation of sample collection methods mean that today, we can not only continue to explore the deep sea environment, but also better grasp the major ecological and evolutionary processes that regulate it. Biological exploration is currently reaping the benefit of developments in underwater vehicle technology and advances in molecular biology, which provides access to the diversity of lifeforms in the deep sea environment without the need for observation.

Fig. 1 – **The manned Victor 6000 ROV, shown here during a maintenance operation on the rear deck of the oceanographic vessel Atalante, is a remotely operated underwater vehicle designed for oceanography research.** The lower part of the vehicle can be adapted to suit the needs of the specific assignment and is equipped with scientific instrumentation. It is capable of working at a depth of 6,000 metres. © J.F. TERNAY / CNRS Photo library. ■

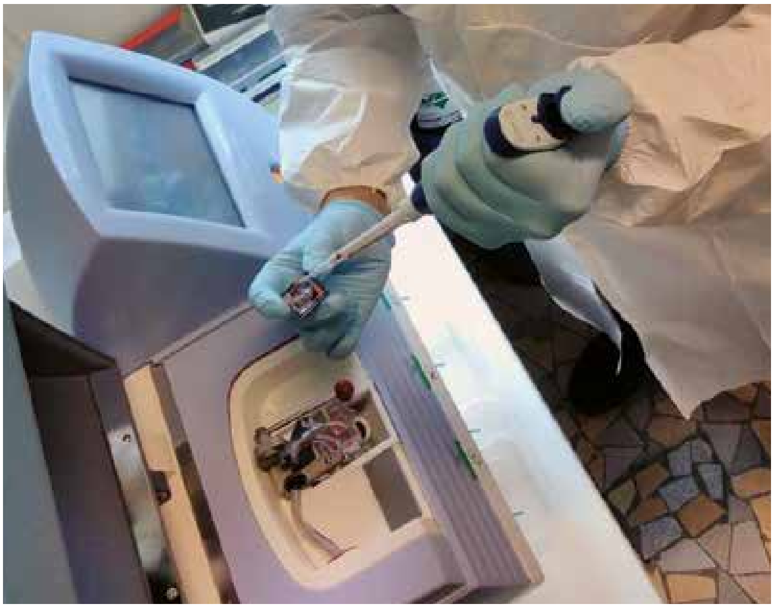

Fig. 2 – **Preparing the next-generation Ion Torrent sequencer for characterising environmental DNA.** © J. ABDELKRIM. ■

Exploration and remote presence

Today's remotely operated underwater vehicles provide a more flexible alternative to submersibles for exploring the deep ocean environment. Controlled from an oceanographic vessel, the vehicles can be equipped to film, photograph and collect samples from the seabed at abyssal and even hadal depths (below 6,000 m), relaying images to the surface during the dive by optic fibre, and even sharing them with research teams who are still on land. These vehicles are a remarkable tool for scientific collaboration and for sharing information with the general public, even with the significant drawback that only a small quantity of biological material can be brought back to the surface. They can be fitted with various kinds of probes (to measure temperature, salinity, dissolved oxygen...) and sampling apparatus (such as a handling arm, a suction sampler for fauna or sediment corers), and can work for several consecutive days, covering large areas (100 km^2 in the case of the French Victor vehicle in Fig. 1).

Working at such extreme depths has its risks: in 2014, the Nereus remotely operated underwater vehicle belonging to the Woods Hole Oceanographic Institution in the US, designed for exploring the deepest regions of the oceans such as the 11 km-deep Mariana Trench, was lost when diving to a depth of 9,900 m. The difficulties faced by oceanographers in developing vehicles capable of withstanding such extreme pressures are not dissimilar to those encountered in astronomy, and knowledge transfer between these two scientific fields is ongoing. One such example is the Helmholtz Alliance 'Robotic Exploration of Extreme Environments – ROBEX' initiative.

Massive sequencing of environmental DNA

In parallel with observational resources, DNA sequencing techniques offer a means of accessing the diversity of lifeforms based on genetic information (Fig. 2). When applied to environmental samples such as water or sediment, these methods reveal the variety of lifeforms without the need for observation. Interpretation of these indirect data is based on comparison with data obtained from known organisms, and their analysis suggests the presence of considerable diversity that does not feature in the available databases. These organisms are often too small to be observed using underwater imaging, though.

If we are to understand these environments, it is therefore necessary to combine observation methods with the collection of samples of lifeforms of all sizes and the indirect analysis of diversity. It is still relevant to take environmental samples using the 'traditional' tools of benthic ecology, such as nets and dredgers, and to increase the number of study sites (as in the example of the Tropical Deep-Sea Benthos programme run by the Paris Natural History Museum and the French National Research Institute for Sustainable Development, the IRD), creating the foundations for interpreting imaging or genetic diversity data. This synergy is an essential feature in the study of marine biodiversity, its origins and evolution.

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17. Marine biodiversity: what is there still to discover?

Philippe Bouchet

In propelling biodiversity into the realm of political concerns, the Rio Convention generated a flood of reviews, summary reports and forecasts of the number of species known on Earth. Unlike entomologists, marine biologists have a tool for measuring the magnitude of marine biodiversity, the World Register of Marine Species (WoRMS). Working with a network of 50 taxonomic editors, WoRMS maintains an up-to-date global inventory of known marine species and their valid names. The primary reason for assigning names, to which biologists and non-biologists attach traits and characteristics, is so that all branches of knowledge can communicate with each other using universal terminology. As of April 2016, WoRMS had identified 239,165 valid species, across all taxa. This level of precision may well raise a smile, but it reflects both the comprehensiveness of the catalogue and the progress of discoveries. Indeed, far from being complete, the rate of discovery of marine flora and fauna shows no sign of slowing, and today, in the early 21st century, scientists are still discovering new species at a pace faster than during the historic expeditions of the 19th century. Since 2010, no fewer than 1,930 new marine species have been described each year!

From discovery to description

Often, many years elapse between discovery and description; for marine species, the average is 16 years (compared with 30 years for plants and 21 for all biodiversity). There are good reasons for this delay. When a specialist has in their possession a single specimen of a species that they believe is new, more often than not they will want to base their description on several specimens. Their discovery is therefore shelved until such time as another expedition collects one or more additional specimens. There are also bad reasons, however. There are entire taxonomic groups (both marine and terrestrial) with no active specialists anywhere in the world: this is the case for many small invertebrates (*e.g.*, crustaceans, molluscs, annelids, nematodes...), while the more emblematic groups (*e.g.*, fish and reef-building corals) are the focus of much attention. For these 'neglected' groups, the road from discovery to description starts on the shelves of the major museums, whose collections offer a considerable resource for research.

Fig. 1 – ***Dinochelus ausubeli*, or Ausubel's Mighty Claws Lobster, a blind lobster discovered at a depth of 320 m off the Philippines and named in honour of the Sloan Foundation's programme officer, who supported the Census of Marine Life from 2000 to 2010. © T.-Y. CHAN. ■**

Location of unknown species

Newly discovered species come from all over the world. It is true that Europe's seas have been the focus of naturalists' attention for more than two centuries, and on the whole their marine macroflora and macrofauna are well inventoried. Nevertheless, meiofauna (small organisms living between sand grains), single-celled eukaryotes and parasites remain under-researched everywhere, including in the immediate surroundings of marine biological stations. However, the major sources of unknown species are the tropics (Fig. 1), specifically the 'Coral Triangle' which stretches from the Philippines to Papua New Guinea and is home to an astounding accumulation of species: one square kilometre of coastal ecosystems in the Coral Triangle is home to more species than the whole of the 2.5 million km^2 of the Mediterranean. Habitats that are difficult to access are obvious sources of discoveries, whether in the mesophotic 'twilight' zone with its low levels of light penetration, in caves, at bathyal depths in 200 to 2,000 metres or at abyssal depths in 2,000 to 6,000 metres. In contrast, and contrary to conventional wisdom, the polar regions and deep-water chemosynthetic ecosystems, which are the focus of numerous research cruises, are comparatively (very) species-poor, with fewer than 1,000 new species having been described since hydrothermal vents were discovered 40 years ago.

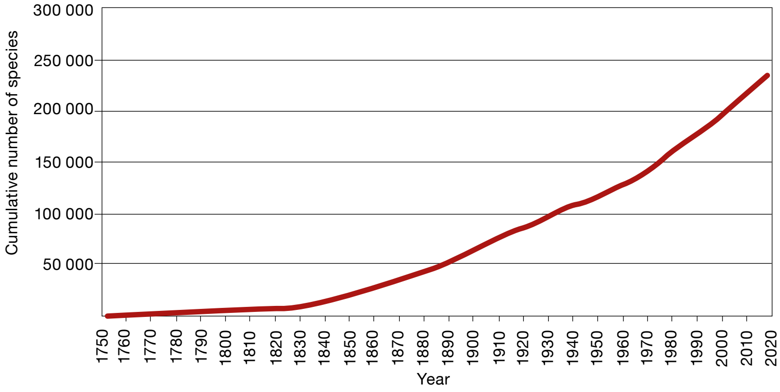

Fig. 2 – **Growth in the number of known marine species from the mid-18th century to the present day.** There has been no tailing off in the curve and most authors speculate that there may be 1.5 to 2 million species in the world's oceans. To date, just 240,000 species have been described and named. Source: http://www.marinespecies.org. ■

Obstacles to the discovery of new species

How many species are really present in the oceans? What still remains to be discovered? With 240,000 species described and a further 2,000 new species being added each year, there is much speculation on the real magnitude of marine biodiversity, with projections ranging from 0.4 to 2.2 million species. The low-case scenario (fewer than 0.5 million species) appears too conservative, and figures of 1.5 to 2 million marine species seem to be a better fit with the pace and number of contemporary discoveries (Fig. 2). Even based on an 'average' hypothesis of 1 million species, it would take 350 years at the current rate of discovery and description for all these species to be assigned a name.

The obstacles to increasing the speed of discovery are primarily scientific and technological. For example, 15 years after the emergence of the 'barcoding of life' concept and the launch of major sequencing programmes (Marine Barcoding of Life and International Barcoding of Life), it must be acknowledged that the objectives announced with such initial enthusiasm have not been achieved: to date, barely 10% of known marine species have a sequence in the major molecular databases and the percentage is hardly any higher for newly described species. Furthermore, there are also sociological obstacles. Indeed, when a group of marine (or terrestrial) organisms for which no critical monograph has been produced for decades and is in need of revision, more often than not there is no backing for it from funding agencies, on the grounds that exploration and discovery are not sufficiently hypothesis-driven. As a result, there is often no one specialist for the most challenging families of organisms, which are also the major reservoirs of unknown species, and they become what are referred to as 'orphan groups'. Lastly, there is a final, regulatory obstacle, in the form of the Convention on Biological Diversity (1994) and the Nagoya protocol (2014): the collection of scientific samples and their permitted uses are subject to regulation and licencing – which is ethically essential in regulating research for commercial purposes (such as pharmacology, cosmetics or aquaculture), but presents a formidable obstacle in terms of academic exploration.

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18. Plankton imaging

Christian Sardet and Gaby Gorsky

Plankton

Plankton is the term used for the group of organisms that drift with currents and are essential for the equilibrium of the planet's oceans and atmosphere. Plankton range from bacteria and viruses to fish larvae and jellyfish. Plankton are the best example of biodiversity on Earth since all branches of the tree of life (apart from terrestrial plants) are represented. In addition to organisms that spend their whole life drifting, most animal species that inhabit seabeds and coasts are planktonic in their embryonic and larval stages (Fig. 1). The greatest biological diversity resides in protists, unicellular eukaryotic beings. The first global results of the *Tara* Oceans expedition based on gene analysis highlighted the extreme biodiversity of viruses, prokaryotes and planktonic eukaryotes. Although correlation analyses of genetic data can reveal positive interactions between these planktonic organisms, only examinations of these organisms with a range of different imaging methods (optical or electronic microscopy, immunofluorescence and epifluorescence, *in situ* hybridization...) enable us to define the nature of these relations (symbiosis, parasitism, commensalism...)

Fig. 1 – **Plankton imaging.** The largest gelatinous zooplankton organisms can be seen in the upper part of the figure, unicellular organisms (protists), including those of the phytoplankton in the bottom part. Source: C. SARDET, 2013. ■

Imaging the planktonic ecosystem sorted by size classes requires the use of a variety of instruments. Imaging of viruses, bacteria, protists, embryos, larvae and zooplankton has also benefited from complementary advances in optics, electronics, computer science and biology.

Automated imaging

Given the extreme diversity of organisms, only automated imaging analyses of live or fixed planktonic organisms of similar size can provide quantitative data. Automated devices like the FlowCam or Imaging Flow Cytobot, are flow cytometers that generate digital images of objects driven by liquid flow. They can be used to image phyto- or zooplankton organisms between 20 and 200 microns (μm) in size. The FlowCam is a laboratory device, the Imaging Flow Cytobot is a submersible flow cytometer. Instruments such as the ZooScan are used to

Fig. 2 – **Left to right: thumbnail images of microplankton organisms imaged with FlowCam, mesozooplankton organisms imaged with ZooScan, and macroplankton organisms recorded with the Underwater Vision Profiler (these two instruments are distributed under CNRS license).** Zooprocess is an open source image acquisition and processing software designed by M. Picheral of the LOV. © A. ELINEAU, Observatoire Océanologique de Villefranche-sur-Mer. ■

image and quantify fixed zooplankton organisms between 150 and 5000 µm in size, Fig. 2). Coupled with computerized methods of sorting, identification and classifying, these analyses enable the determination of taxa, sometimes species, and the composition of functional groups. These quantitative imaging methods measure the abundance of organisms, the morphometric parameters and the biovolume of various categories of plankton.

In situ imaging

Another strategy is to image the diversity of plankton *in situ* by deploying instruments from boats. For example, the ISIIS optical system is a shadow imaging device capable of visualizing a large volume of water at high speed for zooplankton ecology (> 1 mm). The Underwater Vision Profiler (UVP), is a stroboscopic imaging system that records living organisms (> 0.7 mm, Fig. 2) at high frequency in a precisely known volume of water. While the first system is towed, the second is deployed vertically down to a depth of 6,000 m. Both approaches allow non-intrusive identification of the genus and abundance of organisms present at different depths. A good example of the success of this type of *in situ* imaging approach is the recent discovery of the importance of colonial radiolarians in terms of biomass, as these organisms are generally underestimated and mishandled by conventional collection and fixation methods. The *in situ* imaging of zooplankton visible to the naked eye is also practiced by divers using manned submersibles and ROVs (remotely operated vehicles) equipped with increasingly powerful cameras (high or very high resolution, high sensitivity, sensors capable of imaging fluorescence, luminescence and the temperature of organisms).

The miniaturization of sensors and electronics, the development of autonomous devices and data transmission *via* satellite networks predict a revolution in the use of underwater imaging.

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19. Description of a marine expedition

Catherine Jeandel

The marine environment can only be truly understood through the convergence of several disciplines. Fluid circulates, swirls and transports heat from one side of the planet to the other. Physics and fluid dynamics focus on studying its circulation. However, this fluid is also a chemical solution (cf. II.6), and studying it from this angle requires specific skills. Finally, the ocean is a living environment (from the smallest algae cells to the largest mammals), which requires the expertise of biologists.

Constructing the project

For multidisciplinary marine research expeditions, physicists, chemists and biologists construct a project together and work aboard the same ship, for a duration of up to two months, to collect samples of water, chemical species and living organisms. To better understand the work of these scientists at sea, let us take the example of an expedition researching how carbonic gas of human origin penetrates the Solomon Sea. This is a crucial question, because by absorbing anthropogenic CO_2, the ocean helps to regulate the increase in the atmospheric concentration of this gas, and with it the greenhouse effect. Moreover, it is important to know whether this invasion of excess gas disrupts surrounding life. Therefore, researchers start by identifying key zones, where the physico-chemical and biological conditions suggest particular mechanisms for gas penetration and for what happens to the gas once it is in the water. A scientific project is then written.

The currents are strong in this region, and subject to great seasonal variation. To quantify these currents, physicists therefore need to measure temperature, salinity and oxygen, between the surface and the seabed (to a depth of 6000 m), night and day. These measurements are taken using a dedicated device called a CTD probe, equipped with sensors (for pressure, temperature, salinity and oxygen) and water sampling bottles mounted in a ring on a frame (a 'rosette'). The whole system hangs from a cable which can conduct an electrical signal, and it descends to the seabed with the bottles open. They are closed at specified depths during the ascent. The researchers in charge of the CTD probe's descents and ascents will continuously record the values of the parameters measured by the sensors. There are three people operating this system at all times, 24 hours a day. A total of nine scientists working 'shifts' are dedicated to this task. Moreover, the extreme variability of the current means that anchorages equipped with current meters must be left in place

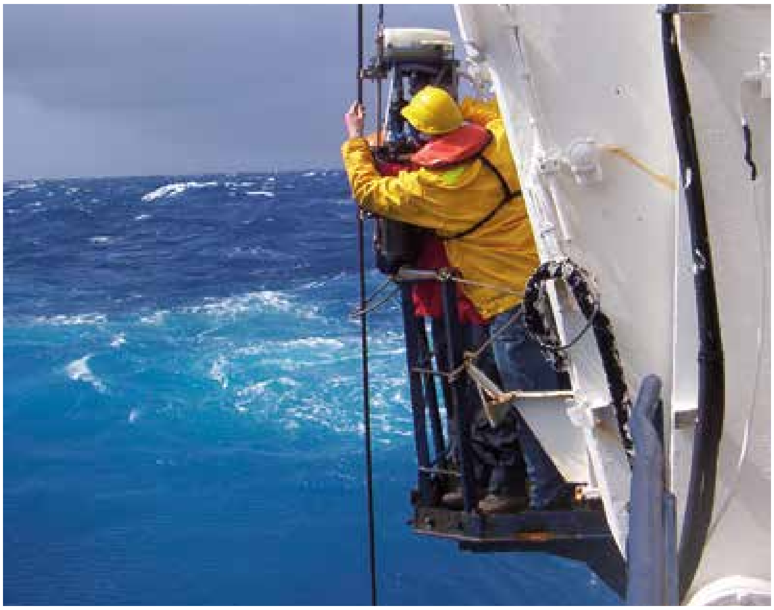

Fig. 1 – Lowering of a pump allowing sea water filtration, from the ship *Marion-Dufresne*. © M. SOUHAUT. ■

Fig. 2 – **Organization of an on-board laboratory.** © C. JEANDEL. ■

for at least a year. These devices are installed all along cables, which are ballasted to keep them fixed to the seabed, and equipped with floaters to keep them vertical. They record the strength and direction of the currents throughout the deployment period. On board, there will therefore also be a team of around 6 researchers and engineers specialising in anchorages.

The bottles on the rosette each bring up around 12 litres of water, which is then sampled by the chemists. Salinity and oxygen measurements are taken on board, in order to calibrate the CTD probe's sensors. Given the subject of study, the whole family of CO_2 derivatives in the water will be measured. Since this region of the world is subject to heavy erosion run-off from the neighbouring islands, this matter will be analysed, and water will be filtered for this purpose. Adapted pumps will therefore need to be deployed. This matter releases nutrient salts which are indispensable for life. Measuring them allows us to understand how plankton develops. Some of these nutrients, such as iron or copper, are very difficult to detect. Specialist researchers and a 'dust-free' room (brought aboard in a dedicated container) are therefore required. In total, around 10 chemists will therefore share the 12 litres of water: 60% will be analysed on board, and 40% will be stored in labelled flasks, for more sensitive measurements which will be conducted in a laboratory on return to land. To describe the chain of life, it is necessary to identify algae species (phytoplankton), bacteria, and the small animals that eat them and lock away carbon by sinking to the deep seas when they die (taking with them a fraction of the CO_2 absorbed at the surface). Dedicated nets must therefore be deployed, so that 8 biologists can monitor the development of the species in laboratories and incubators. In total, 33 researchers and 24 sea crew will work non-stop (including Sundays) to explore the Solomon Sea, collecting samples and taking measurements.

Once written, the project must compete with others, to be evaluated according to very stringent scientific criteria. Expeditions are expensive and 'boat time' is in short supply, so the scientific aspects must be flawless. Once the funds are raised and the expedition is scheduled on the adapted ship, it can finally take place.

The expedition and the return to land

An expedition of this kind requires part of the laboratory to become 'floating', moving aboard the research boat for the duration of the trip. At least three months are needed before departure to carefully prepare the equipment, and 40 m^3 of equipment may need to be sent. On board the ship, laboratories need to be installed and the space needs to be shared… as does the precious water! For two months, the samples are analysed or packaged, and steps taken to ensure their traceability.

The scientific team generally returns exhausted and gets little time to recover, because the samples must be repatriated and processed. The data will be shared at conferences and will be the subject of scientific articles describing the results, as well as the new questions arising from these discoveries. A few years later, these questions in turn will allow the construction of a new project, in the same place or elsewhere… always with the aim of understanding how the ocean works. For example, the analyses of the expedition described in this article showed that anthropogenic CO_2 could penetrate to over 1000 m deep in the Solomon Sea.

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- PART FOUR -

History and representations of the ocean

Previous page:

On-board the Else, a boat used by researchers to observe pilot whales in the Mediterranean.
© CEFE / CNRS photo library / C. FRESILLON. ■

1. Seas and oceans: a complex history

Gérard Le Bouëdec, Éric Rieth and Agathe Euzen

The ocean is a metaphor for the interface between the societies and economies on each shore. Our comprehension of the ocean relies on a form of representation which varies between the different actors. Efforts to map it stem from a desire to claim it, and the history of marine cartography first became that of an empirical discipline, then of a scientific one. Before anything, it requires knowledge from voyages of discovery, exploration and exploitation. The motivation for these cannot be reduced to a yearning for adventure filled with myths and sea monsters, because the hunger of political powers, as well as cultural, religious and economic interests, came into play from the outset.

World map by Guillaume Le Testu, explorer and cartographer born in around 1510 in Le Havre and who died in Panama on 31 March 1573. ■

The resulting 'maritime economy' revolves around three major pillars. The first is ports, from the simple harbour nestled in the coastal landscape to the increasingly closed and inaccessible developed port. The study of these focuses on positioning, access, facilities and functions. Second are maritime journeys and routes. The slow development of these is inseparable from the constraints of the currents, winds and tides, which require constant vigilance, since our technologies cannot deal with all of these risks. To guide navigation, the development of a signalling system using fires and lighthouses has always been required, with constant improvement in techniques. This is the third pillar. Despite these efforts, risks at sea, from sinking to seizure, have not been eliminated. Countries which have made the sea a driver for their development have sometimes attempted to use it as an instrument of power, making the ocean a new territory for conflict and confrontation. Since time immemorial, and in all regions of the world, the ocean has above all been a provider of food: 'the wheat of the sea'. It was these fish resources that human populations first sought out on the foreshore. Then, the peasant fishermen on the shore became sea fishermen when resources ran low, forcing them to search further afield. By travelling to fish cod in Newfoundland or Iceland, they were already looking for an alternative: convinced that the resource was inexhaustible, they used the vastness of the ocean to continue exploiting it. This multi-functional exploitation requires ships and workers. It needs shipyards to build and repair all kinds of vessels, the history of which is traced by undersea archaeology. Behind these navigation companies and the crews, there are investors and ship-owners. The regulation and control of maritime activities are indissociable from the power of the state (whatever its form), of port institutions, and of certification and regulation organizations. However, although this 'maritime economy' has its own dynamics, it exists only to serve the societies of an ever more connected and globalized world.

2. Voyages of discovery

Florence Le Corre

The sea has always been a place of curiosity for men and women who want to surpass themselves. The first journeys of exploration driven by the need to trade, led to the discovery of roads and made it possible to approach and even conquer new territories. From the 18th century on, these journeys became real openings that also led to scientific and ethnographic findings.

Trade

The first commercial journeys were undertaken by the Egyptians in the 3rd millennium BC, then by the Greeks in the 5th and 4th centuries BC, who ventured as far as India. They returned with precious spices that aroused envy and were the reason for many expeditions.

A desire for expansion and conquest gradually motivated maritime expeditions. Soleyman, a merchant from the Persian Gulf, reached China in the 9th century, and Ibn Battuta's journey to Mecca from 1325 to 1354, was an extraordinary way of discovering the countries he crossed, as far away as China. The Vikings sailed to Newfoundland and Greenland, which were colonized by Erik the Red around 982. To assert China's maritime power, Emperor Yongle sent Admiral Zheng He overseas in 1405. He voyaged to East Africa on ships fitted out for trade on seven separate expeditions.

Exploration

From the 5th century onwards, the Christian Church provided a new objective for exploratory journeys: the evangelization of populations, reaffirmed in the 15th century. When the New World was shared between Portugal and Spain by Pope Alexander V in the 1490s – the Treaty of Tordesillas was signed in 1494 – the event encouraged the discovery of new continents, not to mention the search for routes to the Indies. In this way, Bartolomeu Diaz reached the Cape of Good Hope in 1488 and Christopher Columbus, supported by the Spanish crown, reached the Caribbean, Cuba and Santo Domingo in 1492, then Honduras and Panama. In 1497, Vasco da Gama departed for the Indies *via* the Cape of Good Hope and for the first time travelled up the coast of East Africa. He arrived in Calicut on May 19, 1499. On a second journey, he established a colony in India in the name of King Manuel I of Portugal, thereby laying the foundations of the Portuguese colonial empire. Pedro Cabral reached Vera-Cruz in 1500, the Spaniard Ponce de Leon reached the North American continent in 1512 and Hernandez de Cordoba the Yucatán in 1517. The first voyage around the world was accomplished by Magellan, who on November 28, 1520, crossed the strait that now bears his name. France decided to invest in the sea and asked Jacques Cartier to find a route to China *via* the Arctic and to reach the North American continent, but he stopped in the mouth of the Saint-Laurent's River in 1534. In 1590, Willem Barentsz also tried, but without success. In the 17th century, research on the southern continent was the new objective. The Dutchman Abel Janszoon Tasman reached the New Hebrides, Tasmania and New Zealand in 1642. Other later journeys led to the discovery of new territories.

Enriching knowledge

Many expeditions also took place in the 17th century. Beyond exploring the Pacific, these missions were inspired by the Enlightenment philosophy and the desire to enrich the knowledge of the scientific community in many fields: astronomy, mathematics, geography, cartography, botany. They were also better prepared, especially in terms of sanitation. In this context, the British explorer James Cook made

Fig. 1 – *Lantcha*, coastal vessel, at anchor after sailing the straits. *Journey of the corvette La Favorite in 1830, 1831 and 1832,* drawing by François-Edmond Paris. © Musée national de la Marine / P. DANTEC. ■

Fig. 2 – **The *Pourquoi-Pas ?* Boat in the bay of Tasiusak.** © Musée national de la Marine / P. DANTEC. © Photo R. GESSAIN (1907-1986). ■

three trips. He discovered Australia in 1770 and crossed the Antarctic polar circle for the first time in 1773. A remarkable explorer, he returned with a rich harvest of geographical and scientific data.

French maritime policy boomed under Louis XV, who sent Louis Antoine de Bougainville to discover the Pacific. He was accompanied by the physician and naturalist Philibert Commerson, the cartographer Charles Routier of Romainville and the astronomer Pierre-Antoine Véron. He sailed off the coast of Australia to reach Batavia and the Island of France. Besides describing the everyday life in Tahiti, in his opinion, a true paradise on earth, he brought back a herbarium of five thousand plant species, many of which were unknown in Europe at the time. In 1785, Jean-Francois de La Perouse began his exploration of the north Pacific. His journey took him to Chile, Easter Island, Alaska, California, Manila, Kamchatka and Australia, from where he sent home the maps and journals rich in observations that made him famous, although he himself never returned.

Charles Darwin voyaged round the world in five years (1831-36), during which he complied a huge amount of knowledge on fauna, flora, minerals, fossils and birds, leading to his theory on the origin of species. Henry Bates and Alfred Wallace undertook their voyage of discovery to the Amazon and Indonesia from 1840 to 1860. In the same spirit, François-Edmond Pâris made precise drawings and wrote detailed records of the non-European boats he observed during three voyages around the world between 1826 and 1840, inaugurating research into naval ethnography.

Discovering the poles

The following centuries were marked by numerous expeditions to the Arctic (cf. VIII.12) the Antarctic during which explorers to discover the poles. Dumont d'Urville reached the Terre Adélie in 1840 and after several unsuccessful attempts, in particular by Roald Amundsen, in 1905 discovered the northern route to the North American continent and also located the South Pole in 1912. Jean-Baptiste Charcot conducted two scientific expeditions to Antarctica in 1903 and 1909 during which he plotted the coastlines, collected geological objects and recorded his many observations.

Exploratory voyages were organized by sovereigns and by countries who wished to dominate the world. At the same time, they enriched our knowledge, made us discover landscapes, different species and populations. They revealed the wealth of different places, as well as other ways of life. Today, the oceans are crossed with joy and with curiosity, and sadly, sometimes for the purpose of war. They are, forever and again, places where sailors try to surpass themselves (cf. V.17).

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3. Maritime routes around the world, from the Middle Ages to the present

Gérard Le Bouëdec

Maritime routes at the end of the Middle Ages

Between the 12th and 15th century, maritime routes were organized in two independent spaces. To the south of the European continent, the Mediterranean region has become the center of gravity of the economy, where the times of the crusades had given way to that of trade between the East and the West under the control of Genoa and Venice. To the north, on the northern margins of Europe, German Hansa cities, centered on Lubeck, undertook exchanges in the Baltic and North Sea and sent their trading vessels along the salt route from the Atlantic coast, *via* London and Bruges. Meanwhile, the Italian fleets ensured the connection between the Mediterranean and Flanders. Between the 15th and 18th centuries, coastal trade in agricultural food products, as well as in raw materials and textiles began to expand, incorporating river trade with a line of harbors, and the emergence of a few major ports, thanks to the first globalization of exchanges.

Maritime routes in the early globalization era

From the 15th century on, the Portuguese and the Spanish opened new horizons and introduced the national monopoly model. Due to lack of industry in Spanish and Portuguese cities, Iberian fleets leaving for Central and South America opened their holds to textile products from other countries, transforming these routes into a floating bazaar on the way out, and into galleons filled with gold and piasters when the way home, thereby stimulating the entire European economy. The Caribbean sugar route became as strategic as today's petroleum route. The explosion in the consumption of sugar led to the establishment of slave-run plantations, which were the reason for the slave trade from Africa, through triangular trade circuits dominated by the major European slave ports (London, Liverpool, Bristol, Amsterdam, Nantes, Bordeaux, Lisbon) or through bilateral exchanges between Luanda in Angola and Brazil. In the Indian Ocean, which, in the 16th century had been dominated by the Portuguese, modeled on the East India Company founded by the Dutch and other European countries (England, France, Denmark, Sweden) spices, tea, coffee, cotton, silk began to be transported at the beginning of the 17th century. The great distances to be covered to India, Batavia and Canton and the winds (the trade winds in the Atlantic and the monsoons in the Indian Ocean), required stopovers at the entrance to the Ocean Indian as well as armed vessels and large tonnage ships. This first globalization was above all a complementary connection of flows. The increase in the consumption of tea and coffee was indissociable from that of sugar and hence from the slave trade. Indeed, to balance their trade with Asia, European ships first had to load piasters from the sale of European cloth in Iberian America. However, the European focus of this analysis should not allow us to forget that in the Indian Ocean, traffic to Europe only represented a side route from the dense inter-Asian trade, which was largely under the control of local Indian, Indonesian and Chinese traders. While on the other side of the Atlantic, from the West Indies to North America, lateral exchanges between colonies attested to a peripheral attempt to escape bilateral trade relations.

Maritime routes from 1850 to the Second World War

The industrial era saw the explosion of tonnages and flows, with the development of the heavy, coal and raw materials of industry and agriculture (minerals, phosphate, nitrate, wood, oilseeds). In parallel, the transport of emigrants to the new countries expanded and transoceanic links were established first on the Atlantic and then the Pacific, a major innovation in the 19th century. This explosion of traffic was enabled by the emergence of iron, steam and propeller ships, which revolutionized the mapping of sea routes. The opening of the Suez Canal in 1869, which made it possible to reach the East and the Far East without going round the Cape of Good Hope, was another major step. That same year, the American transcontinental railway was inaugurated with the aim of creating a new Asia-Europe route through the Pacific. Before the opening of the Panama Canal in 1914, clippers and tall ships circumnavigated the world on trade routes that passed round the great capes, including Cape Horn. American and European shipping companies controlled the biggest passenger and freight flows, which are still mainly traded on a bilateral basis today.

Maritime routes in a globalized world

After the Second World War, the emergence of America as a world power made sure that the North Atlantic continued to be one of the major sea routes. However, from 1960 on, the maritime space became globalized and, under the influence of the international traffic growth, as well as decolonization and containerization, its center of gravity shifted to East Asia. Today, the main energy and container routes are organized around three poles: North America, Europe and more particularly, Asia. With the rise of Japan, then of Korea and finally of China, the number of container ships exploded in the transshipping ports of Tokyo, Yokohama, Singapore, Dalian, Tianjin, Qingdao, Pusan, Shanghai and Hong Kong. Two main axes are used: one across the Pacific, destined for the ports of North America; and the other to Europe *via* the Indian Peninsula, the Persian Gulf and the Suez Canal, with a series of major transshipping ports. On these ocean highways, dominated by global operators, canals (Suez, Panama) and straits (Ouessant, Bosphorus, Ormuz, Malacca) are strategic points with a high risk of military or terrorist activity, attacks by pirates, and damage to the environment.

Cosco, China owned container ship in Hamburg. © G. LE BOUËDEC. ■

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4. A history of representations of the ocean: marine cartography

Emmanuelle Vagnon

For a long time, the ocean was thought to mark the limits of our world, as an unknown space circling the continents on medieval maps. However, in the age of the great European discoveries, as the ocean was explored, it became necessary to include it in an overall system representing land and sea. Nautical maps produced in the Middle Ages evolved into increasingly reliable navigation tools, making possible the naval might of the great European nations. Nautical maps were first hand-drawn by sailors and craftsmen. Later they were printed and their production gradually entrusted to specialist hydrographers. With today's technology, they are now highly sophisticated instruments.

The earliest representations

The first nautical maps appeared on-board ships at the end of the 12th century. They were known as 'portolan charts' and testify to sound knowledge of the contours of the coast and ports around the Mediterranean, less so of the Atlantic coast.

Rhumb lines, map scale and the names of anchorages marked perpendicular to the shores in red and black ink were characteristic of these maps until the 18th century. In the Middle Ages, they were no doubt used primarily as a memory aid and a medium depicting the political and commercial space. At the end of the 15th century, navigation guides such as the Routier by Pierre Garcie Ferrande, designed for sailors on the Atlantic coast, included coastal profiles showing landmarks, sailing directions and tide tables.

Between the 16th and 19th centuries, nautical maps continued to evolve, in terms of both the global expanse represented and their accuracy.

Navigators and captains kept logbooks containing notes on their positions and sketches of the coastlines. On-land, cosmographers sorted this information and compiled it with earlier geographic sources, explorers' accounts and existing maps, to produce new maps or update older ones. Maps commissioned by royal patrons illustrated the extent of geographic conquests and the balance of power between the major European nations, symbolised by ships and coloured flags (Fig.).

A navigational tool

As sailors increasingly took to the oceans, the mathematical construction of maps evolved, turning the old charts into fully-fledged navigation tools for use alongside the compass, ship log and astrolabe and useful in establishing the ship's position and marking out a route. In the 16th century, 'flat maps' were established using a mesh of equidistant meridians and parallels that did not take the curve of the globe into account. However, they included several scales of latitude making it possible to measure approximate distances near the poles. In 1565, the cosmographer and mathematician Gerardus Mercator put forward an pioneering system whereby the map's linear scale increases with latitude, so the ship's route can be traced by a straight line (rhumb line) crossing the meridians a constant angle. The disadvantage of this representation is that it distorts distances as we approach the poles and it was deemed too complex by sailors. It only really became effective later on, once reliable tools made it possible to determine longitudes.

From the 18th century onwards, new, more reliable measuring instruments were developed, considerably increasing the usefulness of nautical maps in practice. It became possible to determine longitude using stable marine chronometers on-board vessels. Mercator's projections thus entered widespread use while observation and triangulation campaigns improved mapping of the shorelines. Depth measurements taken by probes were also recorded. Map production methods also evolved. Portolan charts were hand-made, drawn on parchment and often decorated by illuminators or artists. They were succeeded by nautical maps engraved on copper then printed on paper at the time of the Renaissance. Map reproduction techniques were based on a system of minutes reworked by hand several times, followed by proofs that were corrected before printing the final map.

Emergence of a discipline

Because of its technical and mathematical nature, the profession of cartographer also changed a great deal in the late 17th century. It was increasingly entrusted to specialist engineers working for the State and tasked with establishing measurements in the field then drafting maps. In 1693, the Neptune françois became the first atlas of nautical maps drafted and engraved on order of the King of France, Louis XIV under Colbert's administration. The French Dépôt des Cartes de la Marine was founded in 1720 and secured a map-making monopoly in 1773. The Service Hydrographique et Océanographique de la Marine (SHOM), a public establishment reporting to the Ministry of Defence, is the successor to these 18th-century royal institutions. The collections of the Dépôt des Cartes were donated to the Maps and Charts department of the French national library in 1947.

Nicolò de Caverio, nautical map of the world, Genoa, ca. 1505. Nautical maps are covered by a mesh of rhumb lines stemming from the wind rose and indicating the main points of the compass. Paris, French National Library, Maps and Charts, GE SH ARCH 1. ■

Gradually, other information of use to sailors was added to maps using new symbols such as contour lines to show depth and underwater relief. Bathymetric maps of the oceans, introduced in the mid-19th century became widespread from the early 20th century onwards, under the auspices of the International Hydrographic Organization in Monaco. The use of computer-assisted cartography has really taken off over the past few decades. It provides multiform, colourful maps that indicate all the maritime data now available to oceanographers. The role of nautical maps has thus profoundly changed. From a sketchy representation of the oceans, serving as a memory aid for sailors and depicting maritime empires, maps eventually became reliable navigation tools that sailors could use to determine their position, mark out a route or enter a port. Nowadays, the latest satellite navigation devices may have challenged the practical role of nautical maps but, paradoxically, modern technologies also facilitate the production of new maps that continue to provide knowledge and enable exploration of the oceans.

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5. Lighthouses: a global infrastructure?

Vincent Guigueno

From fire to infrastructure

Although there are strong and often richly illustrated national studies of lighthouses, a global and connected history on the subject is yet to be written. The only 'global' lighthouse historian is David A. Stevenson, whose *The World's Lighthouses* before 1820 (1959) starts with the fires of ancient times and ends at a point when the world's coasts still had very little lighting. This technical and architectural history does not cover the political dimension of lighthouses, which have always been desired, constructed and lit by a power, be it urban (the legendary Lighthouse of Alexandria, for example), royal or imperial. The extensive maritime trade in the Mediterranean in ancient times meant that fires needed to be lit on its coasts or in its straits, for example in Messina and in the Bosphorus. On the Forum of Corporations (Piazzale delle Corporazioni) of Ostia Antica (the harbour city of ancient Rome), mosaics tell of ancient lighthouses, an idea which the Romans brought from the Mediterranean to light up Dover.

Fig. 1 – **Cordouan lighthouse.** © Dimimist. ■

After the fall of Rome, lighthouses became an infrastructure and a symbol of port cities, for example the Lanterna (1543), which marks the powerful port of Genoa. In the 16th century, the territorial scale of lighthouses changed with the birth of the 'modern' states. The creation of the English lighthouse service, Trinity House, in 1514, was the pivotal event in this change. It was to this corporation, as well as to private companies, that the British Crown delegated the construction of lighthouses and the collection of a tax (light dues) in ports to fund them. With 54 lighthouses in 1800, out of 130 for all the world's seas, the English coasts were by far the most illuminated in the world. In comparison, France only had around 20 lighthouses, mostly built by military engineers (Le Stiff, Les Baleines, Cap Fréhel), with the notable exception of Cordouan (1611), in the Gironde estuary, which showcases the magnificence of the Bourbon dynasty through its ambitious aesthetics (Fig. 1). At the time, the light signal used a coal fire, which was replaced by oils in the 1680s.

The optical revolution

If the 18th century was the Age of Enlightenment, the 19th century was the age of lighthouses. Most of the lights marking today's maritime routes date back to this period. This sharp increase was associated with the emergence of a revolutionary technology in the 1820s: the Fresnel Lens, developed by Augustin Fresnel (1788-1827). This engineer, who trained at Paris' prestigious *École Polytechnique*, recommended using cut glass panels (Fig. 3), to converge light rays from a concentric wick oil lamp into powerful beams. Eager to catch up with England, France formed a Lighthouse Commission in 1811, which proposed an ambitious programme to light up the coasts, using this new technology. In 1861, French historian Jules Michelet wrote that France, 'armed with Fresnel's beam', gave seafarers 'another sky' by which to navigate. The image is inspiring: the lighthouse network was like a celestial system controlled and understood by sailors. The beams

Fig. 2 – The metal lighthouse on Amédée Island, off Nouméa (New Caledonia). © ToucanWings. ■

were no longer fixed, as they had been when lighthouses burned coal. They had a 'characteristic' ('eclipsing' or 'occulting' lights) which could be used to distinguish between them. Their position was marked on maps, which became very precise at this time.

Thanks to the famous Fresnel lens, which replaced the revolving reflectors used by English engineers, France soon developed a private industry which could cater for the French coastal market, as well as producing optics for the Empire and the world's maritime powers. Lighthouses were an excellent 'marker' of France's colonial and commercial expansion, from the Second Empire to the Second World War. The Amédée lighthouse (1865) (Fig. 2), in New Caledonia, the Cap Caxine lighthouse near Algiers (1868) and the Mamelles lighthouse in Dakar (1864) are all architectural and historical landmarks of France's maritime and colonial power. In this same period, major trade routes were lit, for example along the Suez Canal, with one of the first concrete lighthouses built in Port Saïd (1869). Across the Channel, the English also developed a glass-works in Birmingham: Chance Brothers. Their optical components brought light to the British Empire (Canada, India and Australia), which also became subject to the economic model of Trinity House. Today, the world's sea routes are marked by thousands of lights and lighthouses. An academic reference site, *The Lighthouse Directory*, lists almost 20,000 such lights. Every night, they give out a codified signal: one white flash every five seconds, three red flashes every fifteen seconds... these signals are identified in 'light lists', allowing the crew to recognize the land mass that they are approaching.

Fig. 3 – Fresnel Lens, 1894. © Musée National de la Marine / A. FUX. ■

New guidance systems

Since the start of the 20th century, the development of radio navigation has gradually reduced the importance of lighthouses for positioning vessels near the coast. In the 1960s, increased maritime traffic and the accompanying risks of catastrophic collisions or shipwrecks considerably changed navigational safety procedures. Near to ports and in the straits, active monitoring systems, such as radar networks and satellite positioning, began to be used.

Lighthouses, a global infrastructure of the 19th century, became part of our coastal heritage in the late 20th century, thanks to the photographs of Jean Guichard and Philip Plisson, and the films of Jacques Perrin and Yann Arthus-Bertrand. As a result of this popular and cultural recognition, the Tower of Hercules became a UNESCO World Heritage Site in 2009, and the Cordouan Lighthouse looks set to follow...

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6. History of marine resources in the Mediterranean Sea

Daniel Faget

In historical approaches, the fishing world, like other artisanal sectors, is often characterized by its traditions, a set of practices and knowledge dating back to a remote, often undated, period. This almost immovable world is considered to have survived intact until the advent of the industrial revolution, representing a multi-year heritage. Indeed, surviving until the 20th century (the machine age), and using technical practices that were already mentioned in antiquity may well consolidate this static view of the history of fishing practices.

By concentrating their studies on recent sources, most of which were produced after World War II, life scientists have long attributed the depletion of marine resources to the primary role played by the recent mechanization of fisheries. Indeed, the technical changes in European fleets in the 20th century did play a key role in the increase in the total tonnage of fish taken, (from 600,000 tons to 1.2 million tons between 1970 and 1995) and these changes are indeed at the origin of overfishing. However, it is important to evaluate the role played by old fisheries in the overexploitation of the environment, whose effects were first felt in the Mediterranean at the beginning of the modern era. In actual fact, Mediterranean fisheries have been experiencing technical and human disturbances for more than 500 years, and their periodization and their effects on the marine fauna need to be established.

Early signs of impoverishment

The modern period (the 16th to the 18th century) appears to be when human pressure on marine resources first began to increase. Following a long decline in fishing in lagoons and at sea in the mediaeval era, the end of the 15th century witnessed the beginning of most of the technical changes that are radically transforming western fisheries today. The invention of the sardine net, and that of drag nets use in the open sea, soon destroyed the shallowest resources in the infralittoral zone. Due to the weak development of a Mediterranean ichtyoarcheology, we have no depletion markers like those provided by Benoît Clavel for the exploitation of the Picardy foreshore area between the 12th and the 17th century. However, discourse on the depopulation of the waters from southern Italy to the Spanish coast on the eve of the French Revolution, cannot be reduced to mere reactionary discourse. The disappearance of small fishing trades, for example, on-foot fishing and beach seining (Fig. 1), but also the decline of an open sea technique like longline fishing in the first decades of the 19th century bear the signature of impoverishment in benthic fauna. The hostility of fishing communities towards small marine mammals, reinforced after the middle of the 19th century, is revealing in this regard. Massive specialization in catching small pelagic fish was the fishermen's

Fig. 1 – **Seine fishing.** Already used in antiquity, seining reached its peak in the Middle Ages. It was ruined in the modern age by competition from drag nets and set nets. Source: D. DU MONCEAU HENRI-LOUIS – Treaty of Fisheries and Fish History, second part, Neuchâtel, 1769. ■

way of reacting to the reduced profitability of bottom nets. Likewise, if the disappearance of large tuna traps can mainly be explained by the State's determination to re-establish its rights over the coastal zone, the declining productivity of the surviving fisheries bears witness to the gradual distancing of tuna routes from the coast in the final decades of the 19th century.

Current overexploitation

In the same period, the arrival of fishing 'machinery' with the 'mechanical civilization' accelerated overexploitation of the marine environment and affected all its resources. The decline in commercial sponge populations in the Aegean Sea from the 1860s on can be explained by the introduction of the 'feet-heavy' diving suit in the area. The spread along the southern shore of the Mediterranean first of the steamship and then of the explosion-powered ship, soon reproduced the same effects already observed along the northern shore since the 18th century. By 1890, the average size of benthic species exploited in the Gulf of Algiers had decreased. The advent of the ring net in the 1920s, adapted after World War II as the 'seinchole' by Bluefin tuna fisheries, but also the expansion of the use of nylon nets from the 1950s on (Fig. 2), the introduction of the hydraulic winch, and a few decades later, of new detection techniques (sonar, high resolution radar) plunged Mediterranean fisheries into a process of non-respect of maximum sustainable yield (MSY), currently exceeded in the case of 96% of the species exploited in the western Mediterranean basin.

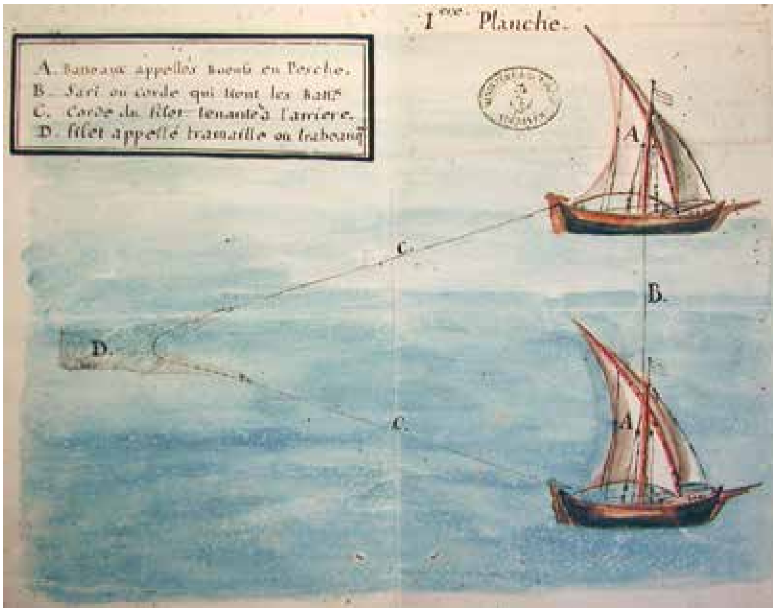

Fig. 2 – **Pair trawling in the mid-18th century.** Pair fishing began at the end of the 17th century in the Ebro Delta as an adaptation of the trawled net used in the open sea as early as the 15th century in the Mediterranean. The efficiency of the net trawled between two small vessels explains both its expansion throughout the 19th century and the reduction of benthic resources of the infralittoral zone. Source: CARAN, C5-35 Mar, 1764. ■

This rather devastating view of the history of Mediterranean fisheries practices calls for three remarks. First, it is important to underline the reversible nature of the logic of unchecked predation that has characterized the relationship between mankind and marine resources in the last few centuries, as evidenced by the success of the 2007 recovery plan for Bluefin tuna, whose estimated biomass increased from 150,000 tons in 2005 to 585,000 tons in 2014. It should also be recalled that the accelerated loss of marine biodiversity is not only due to sea professionals, or sea entrepreneurs. The disappearance of the large colonies of hermelles (small worms) in the Gulf of Marseilles between 1890 and 1914 is not directly linked to professional fisheries, but to the rapid development of recreational boating and fishing, whose current level remains problematic. Finally, the fact that the degradation of resources began a long time ago should encourage us to refrain from placing too much emphasis on the past but rather to work towards establishing regulations that will enable more sustainable exploitation of the riches of the sea.

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7. History of large-scale cod fishing in Newfoundland and Iceland

Jean-Pierre Mélis

Cod, salted and most often dried, is easily conserved and transported, is a valuable nutritional supplement when crops are lost as a result of climatic hazards or during periods of devastation caused by war. For centuries, because of the abundance of cod banks, the coasts of Newfoundland and Iceland have been intensively harvested by European nations, including to a large extent, by France. However, although the two fisheries concern the same fish, their practice and history are different.

Newfoundland and the Grand Banks

According to the most widely accepted hypothesis, it was Basque whalers who 'discovered' the overabundance of cod in the vicinity of Newfoundland in the 14th century. They were quickly followed by the Bretons and Normans, the presence of about 1200 French ships was reported throughout the 16th century, and more than 20,000 vessels in the 19th century. Many ports were at the source of all this activity and, depending on the era, the ports of Saint-Jean-de-Luz, Sables d'Olonne, Granville, Saint-Brieuc and Fécamp, and particularly Saint-Malo made their fortune. However, France was not the only nation to take advantage of this manna, but had to share it with other European nations, particularly with England. Two main types of fishing were used in Newfoundland. The first produced 'dried' cod, which was processed on land shortly after being caught. Basic drying facilities, called 'scaffolds', were built along the coast where the fish were cleaned, salted and air dried (Fig. 1). In addition to the fishermen, this work required a large number of unskilled workers for drying, who were recruited in the backcountry behind the cod fishing ports. This occupation of the coastal territory, shared with the English, led to many conflicts. In 1713, the treaty of Utrecht confined the French to the French Shore, the extent of which was reduced by the Treaty of Paris in 1763. The English never stopped driving the French from the coasts of Newfoundland, whose occupation rights ended in 1904, with the exception of the islands of Saint Pierre and Miquelon, which Louis XVIII had definitely recovered. Gradually driven from the coasts of the island, the French

Fig. 1 – **A scaffold on the coast of Newfoundland in the 17th century.** Source: *General Fisheries Treaty*, Duhamel du Monceau. ■

Fig. 2 – **Fishing schooner in Icelandic waters.** Collection of the author. ■

also practiced green cod fishery, known as ‘wandering fishing’, which is conducted offshore, without landing. At first, men, equipped with a hand line and with one or two hooks aligned along the railing, fished from the edge of the vessel. Then, at the end of the 18th century, they improved the performance of the method by putting boats into the water from the vessel anchored offshore. The boats contained a dozen men who, every day, would let down and bring back up long lines filled with hundreds of hooks. From 1870 on, these heavy boats were gradually replaced by doris, mythical fishing boats in Newfoundland. These small flat-bottomed boats were manned by only two men, which made it possible to multiply the number of stretched lines. However, although the technique increased fishing efficiency, it led to the death of many fishermen who were lost in storms or in mists. When the fish were brought back on board, they was emptied and cleaned, and stacked in the hold between two layers of salt. On returning to France, the green cod, which was only salted, was then placed in drying-rooms to complete its preparation. The cod processed in this way was exported not only to Mediterranean countries, but also to the Caribbean colonies, where it made up an important part of the plantation slaves’ food.

Fishing in Iceland

Following the Dutch, the French began fishing around Iceland in the early 18th century, but this fishery did not really take off until the Treaty of Paris in 1763, which reduced the fishable area around Newfoundland. At the same time, as Iceland was a Danish colony, the French government, which wished to reduce Dutch imports of cod, signed an agreement with Denmark authorizing the French to fish around Iceland and, through economic incentives, encouraged fishermen from Dunkirk to expand this type of fishery, in which they become the specialists. In 1852, the fishermen from Dunkirk were joined by fishermen from the bay of Saint-Brieuc in Brittany, especially from Paimpol, and by the Normans. In Iceland, only ‘wandering’ fishing was possible, as the Danes banned onshore fishing facilities. The depth of the seabed and the violence of the sea made it impossible to use depth lines, so fishing was only carried out using the hand lines from the edge of the vessel. The Bretons and the Normans stored their fish in the hold before delivering them to French dryers. The Flemish, like the Dutch, placed the cod in barrels between two layers of salt. As it dissolved, the salt created the brine that preserved the fish and kept it soft. This kind of ‘packed cod’ was sold on the French market, particularly in Paris, where it was considered a semi-luxury product. The arrival of ice preservation techniques and of railways in the early 20th century put an end to its consumption. Schooners with their topsails were the emblem of fishing in Iceland, the were manned by about 20 men who signed up for a six-month campaign from March to September (Fig. 2).

The arrival of trawlers in Newfoundland like in Iceland, in the first half of the 20th century put an end to traditional fishing. In the 1950s, only the Portuguese were still fishing from dories, while Saint-Malo and Fécamp were the last cod-fishing ports in France.

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8. History of the use of the strand from the middle ages to the present day

Gérard Le Bouëdec

The strand (in French ‘estran’) is the area covered by seawater then uncovered depending on the tide. This word, which is of European origin, also exists in Dutch, German, Danish and Swedish (and is ’strind’ in Icelandic).

Sampling and collection

The sea has always been regarded as a nutritive medium at the service of the land. In regions with dominant coastal agriculture, the sea plays an essential role in agricultural production by supplying manure to strands (seaweed, kelp, sea sand...). In the 19th century, the cultivation of greengrocery products, stimulated by urban demand, ensured the wealth of this coastal strip enriched with the foreshore’s fertilizers, with the sandy cultures of Vendée or the golden belt of northern and western Brittany. The same dynamics prevails today, the SICA platform in Saint-Pol de Leon is the number one in France and the largest shareholder of the ‘Brittany Ferries’ fleet.

The strand is also a food store. Local residents collect shellfish and crustaceans by hand or using small hooks. The collect clams and shellfish by digging the ground with a spade or other utensil. On the mudflats and in the flooded meadows, they catch shrimps with dip nets and eels and aiguillettes with a pronged spear. The strand fisheries are a form of collection organized by the installation of fixed or removable traps. Nearly 400 fish traps were recorded from Bayeux to Oléron in the 18th century. However, these collections can sometimes lead to depletion of deposits, as in the case of oyster beds. For instance, in France, stocks are depleted in the bay of Mont Saint-Michel, the estuary of the Rance, off Saint-Vaast-La Hougue, in the river Seudre, the Gulf of Morbihan and in the Arcachon Bay. Oyster farming, and shellfish farming, a gradual shift from fishing and collecting to farming, is the only alternative when natural deposits are exhausted. The shift from dredging to farming led to the establishment of shellfish farms on the strand.

Salt marshes or coastal gardening

The first form of sea salt harvesting was collecting it in the rocky depressions where salt is deposited due to the evaporation of seawater in summer. The presence of a rational exploitation of salt has been proven in the fifth millennium BC on the Atlantic coast, and from the 13th century on, all low-lying land bordering the French coast between the Loire and the Gironde was colonized by salt-producing farms. In the 18th century, the historian Olivier Chaline assesed the Guérande salt marshes in Arcachon to cover 30,000 hectares, not counting salt from the Mediterranean Sea. A salt production unit includes three types of basin, reservoirs and concentration areas (Fig. 1). The production technique influences the development of marshes. The river Loire is a border between the salt pond system prac-

Fig. 1 – **Saline of Guérande in winter time.** © G. LE BOUËDEC. ■

ticed in Guérande (vast crystallization area) and the area system practiced south of the river (small crystallization area). In the early 18th century, the people from Guérande extended the salt pond system southward, which reached its maximum size in the middle of the 19th century. Salt, scales, carnations, *tremets* or *tessaliers*, ebras, *charraux*, mudflats, *cobiers*, waders, *ladurées* and *mulons*, *bossis* belong to the glossary of the strand shaping by the paludiers and the sauniers. In the Mediterranean, in the region of Peccais, near Aigues-Mortes, the quasi-absence of a tide requires the use of a series of ponds, which serve as salt reservoirs, which communicate with the sea *via* channels.

Fig. 2 – **A beach on the German Baltic coast with its typical *WindKörbe* (wind baskets).** © G. LE BOUËDEC. ■

Salt works are not established on the waterfront in the flooded areas of the foreshore. On the contrary, they are established on previously conquered lands, salt marshes. The bottom of such a protected area is 1.95 to 2.27 meters below sea level at the highest tide reached at an equinox or during the full or new moon. Maintaining salt production is a balancing act between twin perils, flooding which drowns everything, and no sea water, which threatens their existence.

New uses of the shoreline

Beginning in the 1850s, the beach, traditionally used to beach rowboats, dry nets, spread seaweed, collect shells and remove sand, was taken over by bathers. The foreshore was sometimes covered with stakes and ropes to ensure the swimmers were safe, changing cabins sprung up at the head of the beaches and, in the interwar years, beach clubs settled in for the summer season (Fig. 2). The arrival of seaside tourism, which preserved the strand, excluded all the previous activities and reserved it for the exclusive use of swimmers, is at the origin of a of considerable development process. Behind the beach, a promenade was created, if possible shaded, and soon a boulevard appeared to mark the limit of the new neighborhood, at the same time offering vacationers a new space for contemplation. The need to satisfy bather-tourists' cravings for activity was at the origin of casinos. New sporting activities emerged and with them, new dedicated spaces: marinas, yacht clubs, tennis courts and golf courses and racecourses (beaches at low tide are gradually being abandoned by horse racing). Access to the area and the presence of these seasonal populations also changes the hinterland. The construction of road networks, the development of railway services, the construction of individual villas or subdivisions that have be protected against attacks by the sea, the multiplication of palace hotels and big hotels gradually changes the appearance of the sea front, both in small port towns and in rural beach communities. With the development of the residential and nautical economy since the 1950s, the seaside has become home to a population that is increasingly isolated from the former multiple uses of the sea and its strand, by opposing the development of any projects threaten their dream, a gradually constructed image of a completely transformed landscape, a place newly discovered and now refused to the other components of the society.

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9. A brief history of shipbuilding

Éric Rieth

A need for navigation

In France, one of the oldest archaeological examples of a wooden boat dates back to the Mesolithic period (between 10,000 and 5,000 BC) in the form of a logboat dug out of a scots pine trunk of from Noyen-sur Seine (Seine-et-Marne), dated 7,190-6,540 BC by radiocarbon. In Egypt, near the Cheops Pyramid, archaeologists unearthed a complete dismantled ship that resembled a gigantic jigsaw puzzle. Unlike the logboat from Noyen-sur-Seine, which was cut from a single piece of wood, and was 5 to 6 meters long, the Egyptian boat was a wooden hull with an assembled structure composed of hundreds of framework pieces. Dated 2600 BC, the boat was intended to sail on the Nile and is nearly 44 meters long by 6 meters wide. The third example, which left no direct archaeological traces, began in the Neolithic period (between 9,000 and 3,500 BC) with the transport of obsidian (silica-rich volcanic rock) from the island of Milos (Cyclades), through the Aegean Sea to mainland Greece, Cyprus and Egypt, involving navigation either with canoes or rafts. There are many examples, and they all attest to sea, river or lake navigation as early as prehistoric times either directly by archaeological remains of boats or indirectly by objects made from materials whose origin implied navigation.

In all three cases cited above, the vessel or raft was primarily a technical-architectural response to a particular need to move along a watercourse or across the sea for fishing, hunting, religion, or transport. From prehistory to the present day, the origin of a boat, whatever its architecture, its materials, its dimensions, its mode of propulsion, its navigation environment..., is always in line with this same idea of matching a technical-architectural design and a specific application. Of course, the different responses have multiplied throughout history depending on the evolution of societies worldwide, and the evolution of needs and functions of civil or military nature. War has undoubtedly been a determining factor in the need to build boats, but also in the quest for – and exploration of – new territories, for the transport of passengers, scientific research, boating, and offshore racing.

The technical-architectural response

The technical-architectural response, in the case of the monoxyle paddle-propelled logboat with the Noyen-sur-Seine perch, as with any logboat (the medieval Paladru 2, for example, Fig. 1) was removing

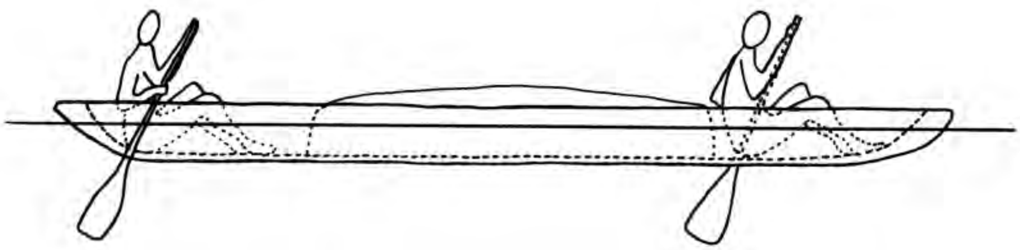

Fig. 1 – **Reconstitution of Canoe 2 from Lake Paladru, Isere dated to the early 11th century.** With a length of 4.82 m length and a width of 62 cm, the maximum carrying capacity of this dugout lake canoe with two men on board was 140 kg. © É. RIETH / CNRS. ■

a large part of the raw material (a tree trunk), resulting in a sealed hull made of a single piece of wood. The main consequence of the relationship of dependence between the 'natural geometry' of the trunk and the 'artificial geometry' of the worked material (the hull) has limited its dimensions (to the scale of the tree) and therefore its load capacities. In the case of the ceremonial Cheops sailing vessel, like in that of any ship with an assembled architecture (Hanseatic hulls, for example, Fig. 2), the objective was to combine an architecture featuring morphologically, structurally and functionally differentiated and assembled elements that would be gathered schematically in three main groups: the longitudinal framework, the transverse framework and the planks. Depending on the era and nautical space concerned (ocean, river, or lake), these three complexes had different architectural relations and also differed in appearance. In some cases, the transverse framework occupied a dominant position in the hull; in other cases, the planks played a decisive role. Assembly, a fundamental technique in this architecture, was achieved in various ways by plant fibers, wooden pegs, tenons and mortises, iron or bronze nails... Wood was the material used to build the Cheops vessel, while other types of materials (skins, vegetable fibers...) were used in different environments, technical contexts and periods. The transition from wood to iron, and subsequently to steel in the 19th century, was a technical-architectural advance of great historical importance that had technical, economic and social consequences (industrial production, manpower). These changes continue today with the introduction of composite materials specially designed for the construction of warships but also designed for pleasure and racing yachts. One fundamental aspect, due to its historical consequences, was that assembly got round the constraints on the vessel's dimensions, structure, shape and carrying capacity. By the end of the 18th century, top ranking warships with complex hulls were reaching 50 meters in length, while today at the beginning of the 21st century, the most impressive liners and container vessels are more than 300 meters long. Finally, the main means of propulsion on rivers throughout the ages were paddling, pole-pushing and towing vessels along a tow-path - while in the maritime environment, it was rowing and sailing. The transition to mechanical propulsion (steam and paddles) in the early 19th century, followed by the introduction of the propeller, the diesel engine and finally by nuclear engines, fundamentally changed the history of shipbuilding and boats, which are not only architectures, but also 'factories' featuring mechanical propulsion and steering systems, and even equipped with weapons in the case of warships.

In all these contexts, technical-architectural responses are based on the knowledge and know-how originating from a technical way of thinking specific to a technical culture and society, that dates back to prehistory and the first dugout canoes.

Fig. 2 – **Replica of the Bremen Kogge (1380), Kiel.** © A. LÜTKENHORST, 2008. ■

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10. The risks of navigation

Olivier Chaline

Risk is the chance encounter between a hazard and one's vulnerability. Because they are often spectacular, 'misfortunes at sea' leave a major impression and may make us forget that boats have long been no more dangerous than any other means of transport. What is more, arriving late or at a location that is not the one where we expected to arrive is not the same as losing one's life and property.

For a sailor or a passenger, embarking means entrusting one's life to a ship. The vessel may be structurally fragile due to errors in the hull's design (like the Vasa, which capsized in 1627), because of the construction materials used, or because of the search for gigantism. Will the underwater parts of the boat resist shocks? Can the vessel be righted? Even in port, a ship can rapidly degrade. In past times, wood rotted, in warm seas hulls were attacked by marine borers (wormlike molluscs), (explaining the interest in copper covering in the 18th century), the hull could distort, letting water leak into the ship, or even be torn open. Our era is characterized by old, rusting 'floating wrecks', that are a danger to their crews and to the coastline, and, in the case of a shipwreck, establishing the responsibilities of the ship owner, the captain... is a real legal headache. When propulsion systems wear out, a mast or a yard may break in the wind or due to strain, maneuvers may be faulty, sails may tear, boilers break down and turbines stop turning. The ship may be delayed, or come to a stop, then be exposed to further dangers. Some cargoes are more dangerous than others, but overloading is the biggest threat, together with poor load distribution, insufficient stowage or too much water in the hold.

Threats from wind and waves

Vulnerability increases with the force of the natural elements. In the past, the wind could interrupt maneuvers, rip sails, damage masts and force the ship to heave to and stand by, shortening its sails to the minimum. In this respect, little has changed today. Waves weakened the hull during pitching or rolling. The question was how to best face the waves, to protect the side of the ship? Some areas and seasons were more dangerous than others: hurricanes are frequent in the Caribbean, cyclones in the Indian and Pacific oceans, and storms are legion in western seas. It was consequently crucial to choose the best time to cross these areas, or leave them in time. But how could a Mediterranean storm be foreseen? To avoid certain capes, like Cape Horn, there was a search for other passages, like the straits of Magellan. The power of the wind is also absolute when it stops: the wind calms, or is not felt, it creates 'lulls', often at the equator. It can also blow in the opposite direction, closing the route to vessels equipped with square sails which are hard to hoist, meaning the ship had to tack. Crossing the Indian Ocean implied adjusting to the monsoon season. However, by the middle of the 19th century, the increase in steam-powered navigation ended the tyranny of the wind. Still, at high latitudes, the sea freezes, pack ice imprisons the ship and can crush it. Like icebergs, which proved fatal for the Titanic in 1912, radar, developed in the 1930s, is the only instrument capable of detecting them.

Fig. 1 – **Landmarks at Pointe Saint-Mathieu (Brittany, France).** © Pline. ■

Avoiding a shipwreck

As French seafarers used to say, ‘It’s the rock that kills’: the coast is more deadly than the open sea. A stranded ship, like the oil tanker Torrey Canyon in 1967, can break in two. Assisting ships in danger, avoiding them being wrecked or evacuating them, are the challenges faced by seagoing tugs today. Fixed ‘landmarks’, meaning visible, have long been necessary to help ships land (Fig. 1). Since the 19th century, lighthouses have pierced the darkness along the coastline. When a sailor can no longer see anything, doesn’t that mean the ship is already aground? For a long time, nothing matched depth soundings, which gave the depth and indicated the nature of the sea bottom. When the sky and the horizon disappear, finding the way depends on the seabed. Being able to identify one’s position accurately was the result of extended efforts. In the second half of the 18th century, navigators used the first marine chronometers for longitude, but their use did not spread until later. In the 19th century, thanks to advances in hydrography, charts and nautical instructions made navigation safer. Even in French waters, it will take a long time to find unknown basses. The use of GPS to determine one’s position at sea, depends on the location of a satellite, spread rapidly in the 1990s. As long as there is no interference, the accuracy of GPS reduces risks.

Human hazards

We should not ignore the role played by humans in the perils of navigation. A ship’s master may lose control of the ship for a material reason (damage or fire), may have to deal with a mutinous crew (such as, in the past, the refusal to obey by private crews who were disappointed after an unsuccessful campaign) or revolts by passengers (sometimes forcibly embarked, like in the case of slaves being transported from Africa). Whether it is finally the cause of a collision or shipwreck, human error originates in incompetence, inattention, fatigue… but can be avoided by training, rotating shifts, assisted piloting methods, or an external control system. Humans have also been predators, practicing piracy in the Mediterranean or in the Caribbean, and today off the coasts of Africa (Gulf of Guinea and Somalia), or in the Straits of Malacca. The war on trade was waged by pirates, then during the two World Wars, by submarines. Patrols, convoys and punitive expeditions have been the responses used over the centuries. The 20th century witnessed the birth of anti-submarine warfare, from the depths of the ocean, at the surface, or from the sky. With the increasing power of warships, close contact engagements, and later, in the 20th century, from increasing distances, destruction of the enemy by cannon, plane and missile, or by fire or shipwreck, has become much more common. From the wooden ramparts of the 17th and 18th centuries to today’s electronic anti-missile countermeasures, the projectile’s race to its target continues.

To reduce risks at sea, prayer is always an option (Fig. 2). An alternative way to arrive safely at port is to apply preventive measures, and register one’s boat.

Fig. 2 – **The *Ex-Voto*, oil on canvas by Ulysse Butin (1880), Palais des Beaux-Arts of Lille.** When a sailor was in danger, he would appeal, for example, to the Virgin Mary and, on his safe return, would make an offering of a replica of a boat, a painting, or a part of the ship. Like in this painting, the church received offerings from the sailors or their families. ■

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11. War at sea through the ages

David Plouviez

Who might wage war at sea?

Quite apart from the technical issues that have determined the forms of naval engagement down the ages, war at sea is a military commitment requiring huge human, financial and material investment, distinguishing it from land war. While some naval skirmishes may involve just a few units, decisive battles, in contrast, call for the use of resources on a grand scale. For example, the Battle of Actium in 31 B.C. (off the coast of Greece and a victory for Octavian) probably involved 700 to 900 ships and nearly 200,000 men. More than a thousand years later, in 1340, 440 ships and 40,000 fought in the Battle of Sluys in Flanders (where the English were victorious), marking the first significant naval engagement of the Hundred Years' War. Though the numbers of personnel involved gradually declined thereafter, technological progress kept fleet costs high. Modern battles, such as the Battle of Navarin on 20 October 1827 (fiugre 1) pitted one hundred ships and 30,000 to 35,000 men against each other, while on 1 June 1916, the biggest engagement of the First World War, in Jutland, brought 149 British warships into conflict with a 99-strong German fleet in the North Sea.

The iccasional mustering of a naval force and, to an even greater extent from the 16th-17th century onwards, the maintenance of a permanent navy, meant putting appropriate financing tools in place (taxation and loans), mobilising manpower (by recruiting sailors), and developing skills (in shipbuilding and infrastructure construction), which only some powers had the means to achieve. In many respects, the processes of development of the nation state and the ability to maintain a navy were linked. In Egypt, the Fatimid caliphs succeeded in developing a powerful navy in the 11th and 12th centuries, making use of the income from natron mines to pay sailors and introducing the Matjar, a complex system of taxation of products sold in the country by foreign merchants. In the 18th century, Britain's Royal Navy was built on a similar tax system, based on heavy taxation of the British and a combination of taxes and customs duties on essential products and services and trade in commodities from the colonies.

Fig. 1 – **Battle between the Bayonnaise and the Embuscade (1798).** © L.-P. CRÉPIN, preparatory sketch, 1799. ■

An increasingly complex military tool

The reason for this differentiation of the powers capable of protecting their coastlines and exploring overseas was the gradual increase in warship complexity, in connection with the technological environment and with backers' strategic and tactical choices. Though ships specially designed for war were a feature of ancient times and the mediaeval period, warships only emerged as a specialization in the 16th and 17th centuries, when artillery was introduced. The ship ceased to be used as a tool for ramming – although the ram affixed to the prow came into use once more in the 19th century – and a platform for transporting men armed with missile weapons, instead becoming a full vehicle for war, for potentially more destructive fire combat. Adaptation of the cannon for use on board ships was a long process that started in the 15th century and was completed in the 17th century, which saw the consecration of the wooden sailing warship as a specialization and squadron warfare (where a group of ships is commanded by an admiral) as a preferred form of confrontation. Up until the 20th century, this set-to between two enemy fleets appeared again and again as the quickest way to achieve dominance over maritime spaces. It was to this end that boarding, as seen in the attack by the Bayonnaise on the Embuscade in 1798 (Fig. 2), gave way to cannon bombardment of the adversary. There was a steady improvement in warships with the advent of the steam engine and high explosive and armoured rounds, a new adaptation fostered by the progress in metallurgy during the second industrial revolution. In 1858, the French engineer Dupuy de Lôme began work on the first armoured frigate, the Gloire, in Toulon. This innovation was quickly adopted by the United Kingdom and the other maritime powers of the age, who engaged in a naval arms race up until the First World War. These developments considerably increased the cost of building and maintaining ships and required the attendant infrastructure to be available: arsenals, for ship building, maintenance and fitting-out; and base stations throughout the world to ensure refuelling and repairs. From the end of the 17th century, the possession of colonial empires by the European powers globalised war at sea. Regardless, these technological upheavals did not substantially change the long-term targets that were set for navies. Ownership of a battle fleet was legitimized by its ability to protect the coastline from invasion, blockade its adversaries' ports, escort trading ships to prevent predation and ensure the projection of force to all four corners of the globe. Commerce raiding, which consisted of commissioning privateers to plague enemy trading ships, could be an addition to these standard missions. Since the end of the Second World War and the emergence of nuclear weapons, all these dimensions have been subject to question. Direct conflict between fleets in squadron warfare has tended to disappear in favour of navies with ships of smaller tonnage, capable of rapid intervention in regional theatres of operation, to carry out security and protection missions (against piracy, for example) or to deploy forces in order to re-establish peace. Furthermore, as stealthy, long-range vessels, navy submarines now serve as nuclear deterrents.

Fig. 2 – **The Battle of Navarin.** © I. AÏVAZOVSKI, 1846. ■

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12. Underwater cultural heritage: a resource under threat

Michel L'Hour

'The best-stocked museum of antiques is as yet inaccessible: it's at the bottom of the Eastern Mediterranean... As we wait for the scientific advances that will enable its proper study, it is to fishing and sponge diving that archaeology owes its magnificent discoveries under the sea'. Sustained by an unwavering conviction and a stimulating confidence in the future, French archaeologist Salomon Reinach uttered the above observation in 1928 and his intuition has since been amply reinforced. Indeed, five decades of professional underwater archaeology have thoroughly confirmed it! Without a shadow of a doubt the world's greatest museum resides at the bottom of our oceans, lakes and rivers; and it is there, in that secret watery universe, that the most important archaeological discoveries of the future are likely to be made. Submerged artefacts are the faithful projection of mankind's seagoing adventures across the globe: they can reveal a particular page in the history of shipping, an example of trade, an overview of technological progress at a given point in time, or perhaps intimate – even indiscreet – insights into cultural and religious practices. Neither the public nor those who govern us are always sufficiently aware of this glaringly obvious fact.

A heritage in need of protection

The archives that humanity has over the centuries consigned to the water are sadly, in our present time, under grave threat. They are faced almost universally with the relentless appetite of economic and industrial activities, frequently subjected to outrageous looting, stupidly delivered into the hands of greedy commercial concessions, and scattered pitilessly in all directions by fishing trawlers as they scour the bottom of the sea. What renders this situation even more tragic is that this extraordinary and fragile heritage, which little-known, neglected or lost civilizations and societies have entrusted to our present time for the instruction of future generations is – like so many of our resources – limited and irreplaceable. Consequently it is our responsibility, both individual and collective, to ensure its protection, to analyse the lessons it teaches us, and to guarantee its conservation. Moreover it is one of the most important tasks required of us, a challenge which our societies cannot, in all good conscience, ignore. To do nothing to secure and promote our underwater cultural heritage would be to admit that our shared history has, for us, little significance. Yet, as we all know, any civilization foolish enough to deny the lessons of the past should fear for the future!

Fig. 1 – Cargo of lead ingots and amphorae from Baetica, on the Sud-Perduto 2 Wreck (AD 1).Corsica, 1989. © A. CHÉNÉ / CCJ–CNRS. ■

Sunken cargoes (Fig. 1) and submerged cities, Spanish oil jars and Chinese porcelain, proud warships and the twisted keelsons of wingless aircraft, works of art inspired by forgotten cults and the heart-rending remains of a D-Day scheduled for the summer of '44... Such are the relics that constitute the extraordinary and fascinating procession of witnesses to another time which flipper-footed archaeologists are tasked to safeguard and champion.

Marine archaeology

For so very long unreachable, the world of cultural maritime heritage gradually became accessible to research during the 1950s thanks to the aqualung, the self-contained breathing apparatus developed in France by Jacques-Yves Cousteau and engineer Émile Gagnan. There soon followed in the roads of Marseilles, off the island of Le Grand Congloué, the first ever scientific excavation beneath the waves. Conscious of their country's status as the founder of underwater archaeology, the French authorities – and in particular André Malraux – decided to nurture this nascent discipline with the creation in 1966 of the world's first official department charged with administering and studying the sunken history of all the waters under its jurisdiction. Based in Marseilles and reporting to the Ministry of Culture, this pioneering underwater archaeology research department – and still one of the few of its kind in the world – is known as DRASSM (Département des Recherches Archéologiques Subaquatiques et Sous-Marines) and has, for over fifty years, been leading the field in the discipline. In the course of the preceding half-century DRASSM has learned how to locate and assess potential sites, design and refine research procedures, improvise and develop excavation methods, bring looting under control, impose a code of ethics and, last but not least, establish and professionalize the domain of 'wet archaeology'.

Fig. 2 – **Humanoid robot Ocean One operating on the wreck of the Lune (1664) at a depth of 91 m, a piece of Catalonian pottery in its left hand. 2014 excavation, M. L'HOUR.** © F. OSADA / T. SEGUIN (Drassm). ■

It was a huge responsibility. Possessing the second-largest maritime area in the world, amounting to a colossal eleven million square kilometres distributed across the Atlantic, the Pacific, the Indian Ocean and the Mediterranean, France probably holds within its waters some tens of thousands of underwater cultural heritage sites. Just taking into account its geographical position in Europe, at the interface between two of the world's major catalysts of maritime tradition that are the enclosed Mediterranean and the open Atlantic, France concentrates shipwrecks from every horizon: Greek, Etruscan, Roman and Saracen in the East; Celtic, Viking and the fleets of the East India companies in the West.

Obstacles to Exploration

The greatest obstacle the world ocean places in the path of the archaeologist is undoubtedly its depth, which casts an impenetrable cloak over some of the best-preserved wrecks. By pursuing technical innovations to help them conquer this final frontier, DRASSM archaeologists are drawing inspiration from the discipline's pioneers (of whom they are the indisputable heirs). Various partnerships with robotics experts have in recent years produced ingenious prototypes, including a humanoid (Fig. 2). Through numerous trials and experiments these machines have learned to navigate the chasm below the sea and, most importantly, to imitate the flesh-and-blood archaeologists for whom they will soon be the docile avatars. The millions of wrecks that lie on the global ocean bed are waiting patiently for the scientists who can deploy the expertise to study them and protect their integrity for future research. Disruptive innovations are, at last, starting to deliver the necessary technology and, as a result, archaeological science is steadily making inroads on the most extreme of environments. Whether on land or in the submerged worlds, whether in dry deserts, on abrupt mountain sides or at the bottom of deep marine trenches, the archaeologist, that attentive and enthusiastic interpreter of a society which never ceases to evolve, is entrusted with the heavy responsibility of translating a mother tongue common to us all. A language we call 'human history'.

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13. The ocean, between gods and men

Alain Cabantous

The ocean drives practices and behaviors that often endure irrespective of the cultural references involved. This applies to sailors' religious attitudes, still in evidence at the end of the 19th century, and even beyond. Such attitudes were strongly influenced by two characteristics of the ocean: the unknown and risk (cf. IV.10).

A world of terror and perdition

The unknown, that is to say, the depths of the ocean, long shaped the religion of seafarers. In the Greco-Latin world, there were specific marine divinities, including the 'primordial divinities' Pontos and Okeanos. Among the gods of the pantheon, Poseidon (Neptune) reigned over the waters, but Dionysus and Aphrodite, Astarte or Fortuna Redux also had the confidence of ancient mariners. Of course, the presence of these deities in no way prevented the abysses from teeming with monstrous creatures that threatened the lives of navigators. Such a configuration of the depths is only partially reflected in the annals of Christianity (Fig. 1) or of Islam and is a kind of incompleteness of Creation, often interpreted as a sign of abandonment of the bottom of the seas by the divine. God appeared to relinquish the Deep to the Devil, who consequently reigned alone over these hellish abysses. This is one reason men were so afraid of dying at sea, for their bodies would be delivered to the demonic domain with no hope of rest. It was therefore not unusual for the maritime populations along many European coasts to invent funeral practices, such as digging fresh graves on November 2, so the souls of these dead might find repose there and rejoin the community.

In turn, the surface of the ocean forged other beliefs. Its peculiar geography, in which mysterious enchanted islands and the Dark Sea co-existed, places of possible perdition or transgression, extended to the vast and endless ocean, isolating the crews from earthly temptations, where the spiritual dimension prevailed. But it was in the light of the many navigational dangers that the main religious practices took shape. The painted votive offerings of Modern Europe, dedicated to a saint or to Christ (in the Protestant world), clearly illustrate the violence of the elements that have to be faced, but also the effective intercession of the saints to whom they appealed: Saint Nicolas, Saint Peter, Saint Ann and most often the Virgin Mary. Despite Erasmus' sharp criticism of haggling between men and heaven, especially in his colloquy '*Le Naufrage*' (The Shipwreck), such beliefs and practices were prevalent in ancient times and prevailed long after, without particularly distinguishing sailors in this appeal to the divine (Fig. 2).

Fig. 1 – **The Biblical character Jonah is swallowed by a great fish for refusing to do God's will.** Metropolitan Museum of Art. ■

Religious practices

Nevertheless, sailors are rather singular believers. Especially at the end of the medieval period and in modern times, with the increase in the amount of time spent on the sea, in the number of voyages and, consequently, their repeated absences, they became atypical parishioners, far from the obligations imposed on ordinary Christians. Their ceaseless confrontation with the real dangers of the ocean obliged them to adopt more protective rituals than any other social group. Like Greek and Roman sailors, who sacrificed an animal before embarking, their distant descendants in Ligurian or Campanian ports did the same until the early 16th century, by slaughtering a white sheep whose skin was nailed to the mast. Less bloody but equally ancient, a painted reproduction of an oculus to ward off misfortune, was observed both in ancient Greece and in the possession of Portuguese fishermen in the 20th century. Similar gestures have accompanied the launching of ships, which, from ancient times to the present, receive a name and a particular blessing. Pious phrases (Allelujah, '*Praise God*') are written on the stern of many Arabian boats. Many ships, including Roman vessels, had a small oratory. However, with a few exceptions, it was not until the middle of the 19th century that the sea blessing ritual began to spread, originally in ports devoted to cod fishing in Iceland or Newfoundland (cf. IV.7).

Fig. 2 – **Votive offering to Our Lady of Laghet (La Trinité, Alpes Maritimes).** © FRANTZ-SAMY. ■

While pilgrimages or collective celebrations before the departure were rare, the habit of taking a protective object on board (magic lead tablets for the Romans) was very widespread. In the 17th century, Christian Mediterranean sailors rarely embarked without a book of the Gospel or pieces of bread blessed on Christmas Eve they would throw overboard to calm the waves. Others carried statues of saints to throw into the water to ensure a good fishing catch. Protestants sailors from Danzig and Lübeck would secretly take an *Agnus Dei* and other religious image with them onboard. But between the 16th and the 18th century, logbooks and votive offerings revealed that resignation and surrender to the divine omnipotence in the face of danger was tending to be replaced by salvation schemes. A sort of 'Heaven helps those who help themselves', in which prayers were saved for the last minute.

Under Christianity, a Christian sailor's religion was primarily secular. Far from clerical and parochial structures, seafarers seldom benefited from the presence of a chaplain. It was the captain who, equipped with appropriate liturgical texts, led the daily prayers and the Sunday service, activity permitting. It was he who presided over burials at sea, and he who, like Christopher Columbus on his first voyage, took a vow. On their return to land, these 'men of absence' attempted to find their place in their community, a community that, in their absence, had celebrated the great religious feasts, taken part in processions, and followed religious education. As if, on land or at sea, the impact of the ocean on the body and on the minds never ceased to nourish and shape seafarers' beliefs.

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14. Myths, monsters and divine beings of the ocean

Agathe Euzen

Vast and imponderable, the expanses of the seas and oceans were long uncharted. Their changeable disposition, at the mercy of the winds and the heavens and harbouring dark and sometimes sinister depths, was a source of inspiration for many myths, legends and mariners' tales. The depths of the oceans were home to strange and fabulous creatures, often thought of as monsters because of their great size and their hybrid nature. These objects of fascination, disquiet or attraction were a feature of old nautical charts (cf. IV.4).

Deities of the seas

The sea had no visible bounds and was therefore envisioned as a large river encircling and circumscribing the Earth, into which all other rivers flowed. Up until the 5th century B.C., Oceanus was considered by the Greeks to be the eldest of the Titans, the son of Uranus (the Sky) and Gaia (the Earth), before he came to represent the realm of the sea. In mythology, Poseidon, the Greek god of the seas and oceans (Neptune to the Romans), was the son of Cronus and Rhea. As the master of the sea, he could conjure up thunderstorms, high winds and earthquakes. He was often depicted as an old man sporting a trident and riding on a chariot pulled by horses or seahorses. He was sometimes accompanied by a monster or by a procession of Nereids, 50 nymphs who were his granddaughters and the daughters of Nereus, a patron god of mariners, and Doris. While they were generally benevolent and helpful to sailors, they could also be fearsome. They had long hair adorned with pearls and lived in their father's palace at the bottom of the sea, where they spent their time spinning and weaving, playing music, singing and entertaining themselves. As daughters of the ocean waves, they were sometimes identified as mermaids living specifically in the Mediterranean and Aegean seas.

Fig. 1 – ***Odysseus and the mermaids.*** Mosaic in Bardo Museum – Tunis, 11th century. ■

Mermaids

These sea creatures first appeared in the *Odyssey*, by the Greek poet Homer. On Odysseus' return from the Trojan War, he tied himself to the mast of his ship so that he could resist the bewitching song of the mermaids (Fig. 1). In the 11th century BC, the Argonauts, returning from their quest for the Golden Fleece, also escaped the mermaids' call thanks to Orpheus, who drowned out the sound of their voices with his zither. The legend of the mermaids travelled down through the ages and was embellished with popular beliefs, folk tales and a variety of depictions. Presumed to be the daughters of the river god Achelous (or of Phorcys) and a muse, mermaids were hybrid beings, women with the body of a bird. Around the 8th century, they were portrayed in literature as being young women from the waist up, but with a fish's tail. No matter how exactly they looked, they drew sailors in with their beauty, bewitched them with their melodious singing and dragged them down to the depths to devour them. The seductive, maleficent mermaid with long wavy hair had various symbolic interpretations: in Antiquity, she represented knowledge; in the Middle Ages, lust; for Christians, she embodied carnal desire; and during the Renaissance, she was a symbol of eloquence and erudition. In the 18th century, observation by sailors and naturalists' discoveries demystified the legend of the mermaids by connecting them with dugongs and other manatees, sea creatures that were at that time classified in the order of mermaids and whose apparition had been assumed since time immemorial to be a figment of mariners' imaginations. Scientific understanding did not prevent the legend living on through literature, however. The Danish writer Hans Christian Andersen resurrected *The Little Mermaid* in a very different guise. In his tale, she became a virtuous, delicate, lovelorn young maiden and it was precisely this love that was to be her undoing.

Monsters or marine animals?

Despite having been identified by scientists, certain marine animals were still portrayed in literature and/or interpreted by beliefs as immensely powerful sea creatures capable of harming people and other seafarers or, conversely, of protecting and helping them. Armand Landrin illustrated this at the end of the 19th century in *Les monstres marins* (sea monsters), which embraces scientific description along with the imaginary, observation and legends.

One such sea monster was the octopus. While it is virtually harmless and was a symbol of fertility in the Far East and of wisdom in Greek Antiquity, in many tales it is seen as terrible and monstrous. Its sheer size, its reptilian appearance, its fluid movements and its many pulpy limbs rekindled the fires of the imaginary and the fantastic, and the octopus was added to the compendium of accursed beasts. In parallel, the portrayal of the giant narwhal by Jules Vernes in his novel *Twenty Thousand Leagues Under the Sea* (Fig. 2) or the giant white whale in *Moby Dick*, also helped the terrifying image of these sea creatures to endure for many decades.

The shark, often seen by Western societies as aggressive, ferocious and cruel, was considered by Tahitian symbolism as a beneficent creature and was associated with wisdom. It was also found in Polynesian cosmogony, where it represented fertility and exemplified the soul, a source of respect. As the objects of such ambivalence, sharks feature in numerous legends and embody many fears. They are often identified with the bloodthirsty image reserved for them in thrillers such as Steven Spielberg's *Jaws*.

Myths and beliefs

Every one of the folklore and symbolic depictions of marine deities, archaic creatures and imaginary monsters plays a part in societal organisation and practices. Down through every age, they embody the diversity of human relationships with the elements and with nature; they also feature the eternal struggle between Good and Evil and Life and Death. The tale of Jonah being swallowed by the whale is an iconic example of this.

Fig. 2 – **Title page of the Hetzel first edition of Twenty Thousand Leagues Under the Sea, 1871.** Houghton Library, Harvard University. ■

In day-to-day life, every society developed its own rituals and customs for escaping curses and warding off even imaginary spells, and for summoning the benevolence of the world below the waves. These could include making offerings to the sea before setting foot on board a boat, blessing a ship before it set sail and, for fear of provoking misfortune, banning or prohibiting the use of certain words or the presence of objects, animals and even, for a long time, women. Many sailors adorned the prow of their ship with a sculpted, painted wooden figure as powerful symbolic protection or gave votive offerings to churches in thanks for their good fortune at sea (cf. IV.13).

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15. The ocean, its cosmo-mythological representations in the Kiribati archipelago

Guigone Camus

A handful of small islands scattered in the heart of the central Pacific, the Kiribati islands (Fig. 1), long unrecognized, are now among the sentinels of climate change: their low altitude and coral soil can no longer resist the indefatigable rise in sea level. For over a thousand years, groups – formed during the Pacific settlement characterized by notable Austronesian migration – gradually organized a society based on gerontocracy in the middle of the ocean, as eloquently demonstrated by stories recounted by Western travelers in the 19th century. Based on public debates conducted according to rules of precedence – with genealogical village affiliations and extended families – this form of organization continues to ensure the social and ritual stability of the islands, despite the transformations produced by nearly a century of British colonization (1892-1979).

The ocean, foundation of the cosmos

Despite some structural links with Polynesian philosophy, the relative geographical isolation of the Kiribati islands and their condition as atolls, whose narrow strip of coral land is subject to the ubiquitous embrace of the ocean, undoubtedly played a role in the islanders' elaboration a remarkable concept of the cosmos. To a great extent dependent on the integrity of the ocean and the sustainability of its resources, this concept is still very present in both formal group meetings held in the large communal maneaba houses (Fig. 2), and in the smallest details of their daily routine. The historical dimension of the concept is also known to us thanks to the esteem, even passion, it aroused in certain colonial and missionary administrators in former times. A remarkable number of cosmogonic and mythological accounts, as well as genealogies, collected by these enthusiasts of a now outdated ethnology have succeeded in giving Kiribati's oral tradition a seal of historical actuality.

Evidence for the strong attachment of the islanders to their oceanic environment is their daily use of it as a source of food, but also and especially in the place given to it in their stories of the creation of the world. A great number of cosmogonies describe minutely how, from a temporality imprinted by a state of latency, a world of indetermination presents a double characteristic: it is a stone matrix, while being encompassed by it. Only the magic and intelligence of a being endowed with motricity, speech and intuition – the Spider-Ancestor – can break the temporal and material discontinuity of this originally closed world. The rupture leaves room for the great tumult of a cohort of ancestors found in various forms (human, animal, vegetable, mineral, marine, elementary), which, as its auxiliaries, complete the splitting of the matrix into two halves, according to the organizational rules

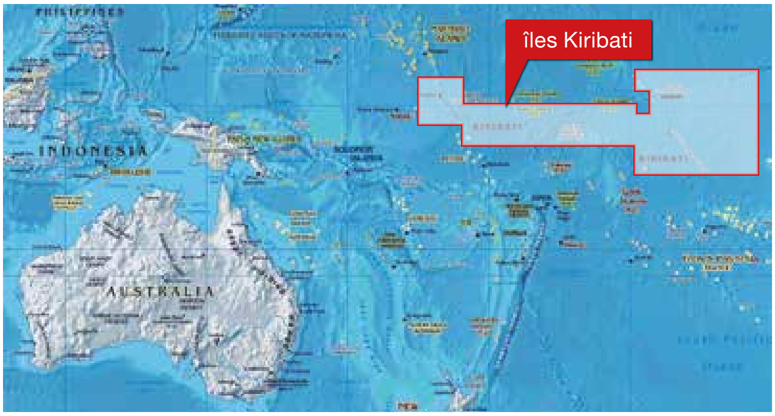

Fig. 1 – **Kiribati is a state made up of three islands in the Pacific Ocean, spanning the equator and the 180° anti-Meridian.** Public Domain. ■

made of complex similarities and oppositions that ensure the stability of the environment.

In a number of accounts, this opening-up of the world under the conditions of divine magic, work and effort, finds a sublime allegory in an analogy between the separation of celestial spaces on the one hand, and land and ocean spaces on the other, as well as the creation of a monumental architecture similar to the great *maneaba*. Heaven, *Karawa*, placed on mythical trees, forms a dome over the whole opposite and complementary Earth *Tarawa*, and the Ocean, *Marawa*. The lights of Heaven, its seasons, its winds, its inhabitants, watch over the abundance of the two other worlds, whose resources are subsequently bequeathed to humans. Thus, in the Kiribati philosophy, this cosmic 'house of the world', which has both a marine and terrestrial base, and a celestial roof, takes on the meaning of a concept the West may not yet be able to grasp, even though it cherishes it: *ecology*, *oikos* (house) and *logos* (discourse).

The imprint of genealogies on the ocean

As the high point of the islanders' passion for their history, recalling their genealogy continues to permeate both memories and discussions. To legitimize the prerogatives they exercise in a village, each individual must be able to list by rote, from top to bottom, the names of mythical ancestors on both his paternal and maternal side, he will have scrupulously selected according to their prestige, the land rights and the ritual privileges they bequeathed to him.

Fig. 2 – ***Maneaba*** **Community Meeting House, Buota village, Northern atoll of Tabiteuea. © G. CAMUS.** ■

In the mind – but also in the written form – such genealogies do not present themselves as trees or diagrams, but as different kinds of narrative rhizomes, a real labyrinth of mythical ancestors' names, to which are aggregated a number of abundantly detailed scenarios. A geographical and historical analysis of this type of family formalization concept makes it possible to uncover the structural relationships maintained by these ancestors on the one hand, and the fundamental place given to their maritime voyages, on the other hand. Before each of these characters enters a matrimonial alliance, fathers one or more generations, illustrates himself by an architectural achievement, a warfare exploit or the deployment of magic power, he must cross the ocean, and follow trans-pacific and inter-archipelagic routes, a multitude of traced maritime itineraries, on which they have sometimes left their imprint by creating, for example, an island or a rock. These journeys, made sacred by human thought and punctuated by onomastic lists, form the 'paths of memory' of a spiritual maritime cadaster.

Regarded as inseparable from the earth in the basic formation of the cosmos, and as a space invested by the incessant work of remembrance of ancestral migrations linking beings in a singular vision of family ties, the ocean remains a place of philosophical inspiration and of collective knowledge, although still quite enigmatic. However, along with the uncertainties attendant on food insecurity and migration brought about by irreversible climate change, the question of progressive 'unpertaining' of a society from an ocean under transformation, perceived as a danger, must be posed by research, given the deep intellectual attachment this environment generates.

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16. The ocean inspires painters

Denis-Michel Boëll

Scenes of navigation painted in the 14th and 15th centuries illustrate travel books from the Légende Dorée (written by Jacques de Voragine in the 13th century), or depict the legend of Saint Ursula, or protective figures who intervene on behalf of sailors, like Saint Nicholas saving vessels from shipwreck. The composition of such scenes, representing dangers and rescues at sea, continued for five centuries in the *ex-voto* tradition of painted offerings destined for the many sanctuaries along the Atlantic and Mediterranean coastlines.

The birth and manifestations of marine paintings

The 'marine' genre was born at the dawn of Renaissance, in Flanders and in the Italian peninsula. In works by the Antwerp artists Joachim Patinir and Herri met de Bles and later Pieter Bruegel the Elder, the formula for a landscape open to the sea appears to be inspired by the Bible (Jonah swallowed by the whale) or by Mythology (the fall of Icarus). Bruegel produced a remarkable series of portraits of ships depicting the famous naval battle in the Straits of Messina. In Italy, Genoa and Venice witnessed the increase in this 'taste for the sea', so much so that at the end of the 16th century, Roman aristocrats' palaces were being decorated with sea frescos painted by Paul Bril and Agostino Tassi. Finally, the naval battle of Lepanto (1571) inspired a host of artists sponsored by Rome, Venice, Antwerp or Bruges.

On the North Sea banks, the emancipation of the United Provinces under Spanish control, and the success of commercial shipping from the East Indies to Asia was celebrated at the beginning of the 17th century by Hendrick Vroom and his followers in the School of Haarlem, then Amsterdam. Then began the Dutch fleet's 'Golden Century', which covered all the different facets of the genre: historical celebrations and naval combats, scenes of flourishing port cities, daily activities on coastal quays and villages, fishing scenes, and the beginnings of sailing for pleasure. The invitation of several Dutch painters, including the Willem van de Veldes, father and son to Britain at the service of the British crown (in 1672), gave birth to a new artistic tradition, which for two centuries, echoed the English domination of the seas.

In France, art, subjected to the rules of the Academy and to the primacy of 'painting history' (religious, mythological or political) fostered an enduring misconception of the maritime world. While the Lorrain Claude Gellée invites the beholder to travel through his idealized port compositions, he himself spent his entire career in Rome, as did later Adrien Manglard, who was received at the Academy with a pair of marine paintings. Still in Rome, in 1753, Joseph Vernet Avignon, received Louis XV's order to portray *'all the ports of France'* (Fig. 1). Influenced by the Italian vedute, his paintings are

Fig. 1 – ***View of the Port of Cette*** **(Sète), by Joseph Vernet, 1757.** Musée national de la Marine. ■

full of realistic details that primarily incline to the political mission of magnifying the maritime prosperity of the kingdom. In his many other marine paintings, as in those of many of his contemporaries and disciples, he expressed a new sensitivity to the marine environment, which proclaimed Romanticism. In the 18th and 19th centuries, the artists who served the English and French crowns were the chroniclers of contemporary maritime history, of the American Revolutionary War, the naval battles of the Revolution and Empire, and of the scientific voyages of exploration to the Pacific or the poles. The adventures of the great discoverers were portrayed in images at the Chateau de Versailles, which Louis-Philippe transformed into a history museum.

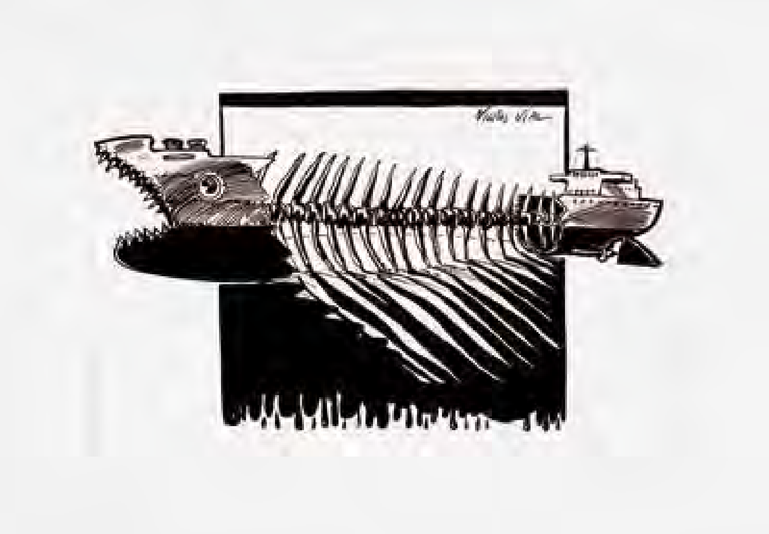

Fig. 2 – ***Oil spill,*** **by Nicolas Vial, drawing published in *Le Monde*, 2000. © N. VIAL. Musée national de la Marine.** ■

Genre renewal

Alongside this commissioned art, with its icy landscapes (Biard, Friedrich), its storms and its tragedies (Gudin, Isabey), the sea became a subject of Romanticism. With the Raft of the Medusa (1819), Géricault renewed both historical painting and the style of the maritime genre. In England, recalling the luminous ambiance of Lorrain, JMW Turner excelled in depicting atmosphere incorporating gales and fog, and in recording momentous events in history like the Battle of Trafalgar (1822-1825), but also the epochal change represented by steam propulsion, as depicted in the Fighting Temeraire (1839).

In the last third of the 20th century, ocean waves crashing against the cliffs of Etretat and the rocks of Belle-Ile, or the littoral as a new recreational territory, became vital motifs expressing artistic modernity: Courbet's realistic depiction of waves, Manet's audacious compositions, Boudin's beach crinolines, prepared the way for the success of Impressionism. Isn't the canvas that gave its name to the movement (Impression, Sunrise 1872) a view of the port of Le Havre? Still, while the abysses were opening up to exploration, and marine fauna and flora were becoming objects of science, the waves remained the place of dreams, from where arise the figures of ancient mythology (Venus, Amphitrite) and the naiads reinvented by literature (ondines and sirens), who inhabit Gustave Moreau's and Odilon Redon's paintings, as those of Böcklin or Burne-Jones.

Next came the time of the navigating artists who were truly familiar with the maritime environment: after the naval architect Caillebotte and the yachtsman Helleu, came Signac, a recreational sailor, who moved from pointillism to watercolor trying to capture the fugacity of light, the furtive movements of the waves and of navigating by sail. In the 20th century, the Fauves caused the colors of the sea to explode, Cubism seized on ports and rigs, and seascapes became more of an abstraction in the work of Nicolas de Staël, while the strong tradition of illustration maintained by 'maritime painters' at the service of the shipping companies competed with photographic images. More recently, contemporary art is again glancing anxiously at the marine world (Fig. 2), a look that no longer expresses fear of the elements, but the environmental threats to the oceans.

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17. Global ocean representations

Sebastian Grevsmühl

In images of planet Earth taken from space, it is often the preponderance of water that impresses us, like in the famous 'blue marble' photograph taken in 1972 during the last Apollo mission. As an icon of environmentalism of the 1970s, this imaginary conjures a 'global view' of our Earth. However, one should bear in mind that no 'global' view can show the whole Earth, only half of it. Of course, cartography was able to solve the problem early on, but the usual maps of the world introduced another bias: they favored the emerged parts of the planet. Indeed, portraying aquatic dominance presents a singular problem because the great masses of water are all interconnected and form a single ocean. For this reason, recent geography textbooks prefer to refer to a 'global ocean', despite the difficulties involved in representing it.

A Systemic Understanding of the Earth

The first representations of the oceans as a single unit appeared in the 18th century. In 1760, the engineer Nicolas-Antoine Boulanger commissioned the engraving of a 'new map' which was very innovative, because it used a projection that was quite unusual for the time. It divided the world into a 'terrestrial hemisphere' and a 'maritime hemisphere' (Fig. 1), on one side, bringing together all the known emerged lands of the time, and on the other, showing the vast extent of our water masses. According to Boulanger, this astonishing distribution could not be a matter of chance, and must be at the origin of a physical law (unknown at the time) of an all-encompassing terrestrial Theory.

Fig. 1 – **New world map by Nicolas-Antoine Boulanger (1760).** ■

Global geophysical observations – that greatly increased in number throughout the 19th century with the institutionalization of Earth Sciences – thereafter promoted an interconnected and global picture of the vast aquatic areas. In the early 19th century, with the work of Alexander von Humboldt, maps and graphs begin to circulate, describing the ocean on a global scale, and integrating a holistic view of the environment. Our present representations rely directly on this tradition of providing logical descriptions of the laws of nature. For example, in recent geography textbooks, the image of the global ocean appears as a visual construction, where land masses are represented in the form of patterns and figures that emphasize mutual dependencies (represented by arrows and feedback loops), often including a strong historical dimension capturing the long history of environmental interactions between the ocean, the continents and the atmosphere.

Overcoming the terrestrial 'bias'

Throughout the 19th century, very few attempts were made to reach beyond the logic focusing on

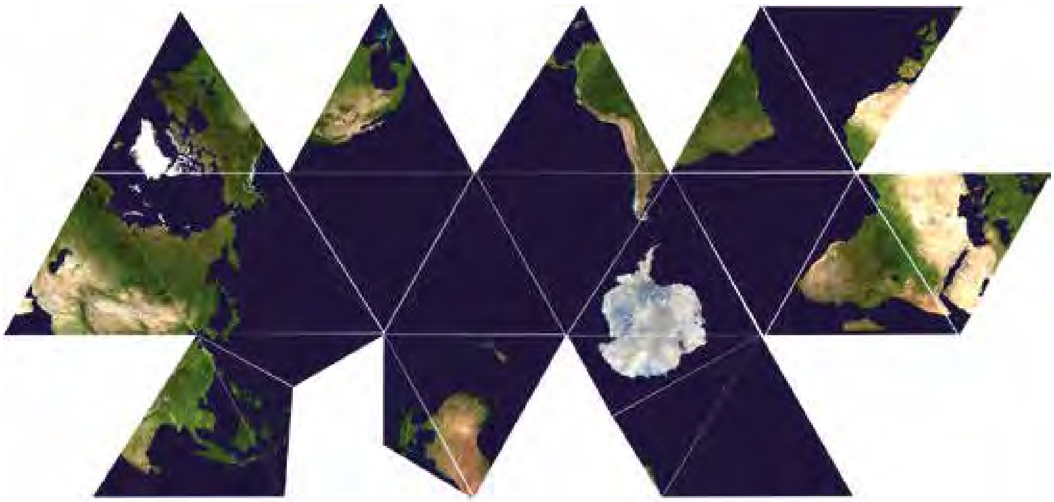

Fig. 2 – **Variation of the Dymaxion map by Buckminster Fuller (1943) showing the global ocean.** ■

the emerged parts of the globe, promoted by the vast majority of cartographic projections, such as the Mercator projection, which remains largely dominant. However, major mapping innovations emerged in the 20th century, allowing for new perspectives of the global ocean. For instance, the Fuller projection (projection of the Earth on an icosahedron surface) was published in 1943 in Life magazine, a huge success with the general public. The 'Dymaxion Air-Ocean-World' map, composed of 20 individual triangles that could be cut out of the magazine by the reader, was the fruit of the imagination of American architect Buckminster Fuller. Having no up or down, and no North nor South, the map can be arranged according to the needs and interests of each user. Thus, it was possible to arrange the individual pieces in such a way as to emphasize the global ocean (Fig. 2). Antarctica appears in the middle of an ocean, itself surrounded by the other continents.

In the same spirit, in 2008, Jack van Wijk proposed another type of projection dubbed 'myriahedral' projection (a polyhedron with a very large number of faces). One of its remarkable applications consists in relegating the continents to the periphery of the map, melting them into a quasi-continuous coastline that surrounds the global ocean (Fig. 3). Finally, more recently, Olivier Serret imagined an elliptical planisphere that retains the surfaces and which is conceived as a model still to be developed. Since the global ocean is represented as a single unit, his planisphere has the advantage of being able to visualize global ocean processes (such as the thermohaline circulation) continuously. Geographers thus still have the will to overcome territorial conventions in favor of a global vision of the ocean, which today, remains an exciting field of research.

Fig. 3 – ***The coastline of the Earth*** **proposed by Jack van Wijk in 2008 with a minimum of distortion.** © J. VAN WIJK. ■

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- PART FIVE -

Uses of the ocean

Previous page:

Toothed fishing dredge and a sailing school in the La Canche estuary, Le Touquet, France. © Ifremer / O. BARBAROUX. ■

1. The growth of maritime uses

Françoise Gourmelon, Chantal Cahu and Agathe Euzen

The ocean is used in an increasing number of ways as technological progress over the past few decades have opened the way for diversification. Although there are regional disparities, it remains that some of these uses have become widespread. They develop near the coast or out at sea. This chapter presents several of these uses, looking in particular at the constraints and challenges they currently face. They are often linked to context and this chapter will not attempt to draw up an exhaustive inventory, taking into consideration their specific cultural, economic, environmental and geopolitical aspects that sometimes result in complex situations to be considered in an integrated, dynamic manner.

It has been acknowledged that certain uses of the ocean provide ecosystem services to our societies, at various spatial scales. However, due to their multiplication and to avoid conflicts in access to resources, a cross-sector planning system has recently been introduced to reconcile these various uses and is applied differently depending on the socio-political context in the State in question.

Berthe Morisot (1841-1895), *La Plage des Petites-Dalles*, around 1873. 24.1 X 50.2 cm, oil on Richmond canvas, Virginie, Virginia Museum of Fine Arts. ■

The search for new sources of energy, for example, is prompting the development of innovative processes and offshore structures. While the harvesting of natural gas hydrates is still at the experimental stage, renewable marine energies are already part of the global electricity supply. This booming sector may end up competing with other, more traditional activities, which are no less important to our societies, such as fishing.

Maintaining fish and aquaculture resources contributes to food security and is actually a major issue in the globalisation of the oceans. This is especially true of small-scale fishing activities around the Mediterranean and in the intertropical region. Fishery and aquaculture production set different challenges in terms of biodiversity conservation and valuation, and hence the sustainable development of the activity. The quality of marine products is also a recent public health issue, linked to the deterioration of the aquatic environment, which receives all kinds of emissions from activities on land or at sea. Global sea transport contributes directly with the pollution it engenders, and indirectly through activity at ports and the ensuing urbanisation.

Increasingly maritime use combined with the growing attraction of the coast for leisure activities have often resulted in uncontrolled urbanisation, which creates new needs, for water for example, and which is now having to deal with the impacts of climate change on weather, sea and demographics. Indeed, while societies are able to benefit from the ocean's biotechnological, mineral and energy resources thanks to active research and technological development, the ocean remains an open, unpredictable yet attractive space to which those societies have to adapt constantly in terms of settlement and practices. The challenge of ocean racing is proof of this...

2. Maritime spaces and their levels of governance

Yves Henocque

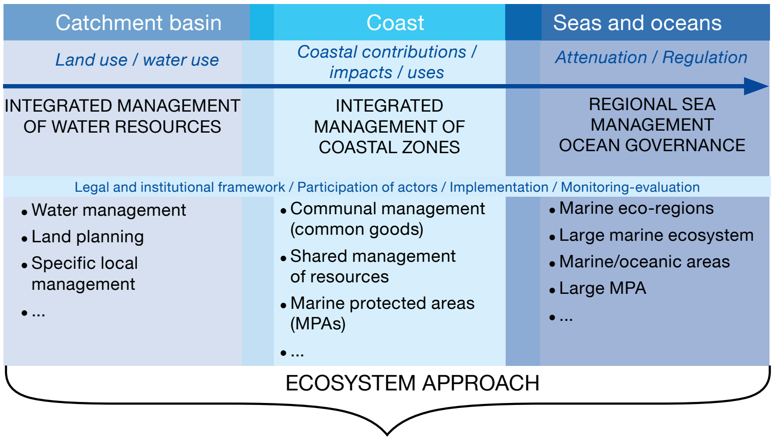
In the ocean and on the coast, global phenomena and their consequences are exacerbated (climate change, bio-invasion, waste, pollution, piracy, migrations...). Responses to these problems are applied locally, but they need to be approached globally. They require shared governance, which implies coordination between state, inter-state and supra-state players, as well as cooperation with non-institutional players. The awareness of the global stakes and the role of the seas and coasts is recent and widespread. It is embodied in the mobilization of science, law and technology to create tools for effective governance in a changing and uncertain world.

From coastal heritage to the ocean planet

About 50% of the world's population lives in the coastal zone, which makes up around 10% of the Earth's surface. This puts huge pressure on coastal habitats and resources. Moreover, a large part of the global population depends on the oceans for food, disposal of waste and waste water, energy production or maritime transport. For many people, the coast is a source of inspiration and a favoured leisure space. Managing these multiple usages and the expectations of an ever-growing coastal population is a major challenge for all countries, both developed and developing.

Further offshore, the 1982 Convention on the Law of the Sea recognizes the freedom to use waters outside the exclusive economic zones of nations. These waters cover over 60% of the Earth's surface. This freedom of use (which includes fisheries, shipping and the burial of undersea cables) is accompanied by duties. However, there is no coherent global system to ensure that states and the vessels flying their flags respect these commitments. There are only separate agreements and organizations to deal with ship discharges, oil pollution and telluric pollution, or different organizations handling fisheries for tuna and other species, as well as different organizations in different regions. There is very little or no coordination between these organizations, implementation of the commitments remains uncertain, and there are still major weaknesses in the system. This leads, for example, to chronic problems of illegal, unregulated and unreported fishing activities, which account for around 30% of global catches (cf. V.8).

The absence of an overall governance system means that, despite the progress made since the Convention on the Law of the Sea was introduced and the ocean was recognized as the 'common heritage of mankind', there is not yet any coordinated, international mechanism to ensure the coherent management of all marine



Maritime spaces in a land-sea continuum. Interconnection of socio-ecosystems. © E. GODET / Y. HENOCQUE. ■

AN EXAMPLE OF CROSS-BORDER DIALOGUE

The Caribbean Sea Commission was created in 2008 by the Association of Caribbean States and its partners, to promote and oversee the sustainable use of this sea. The creation of the CSC was driven by the need for a forum allowing informal dialogue between states on cross-border co-operation between exclusive economic zones, but also including international waters, to establish a coherent governance and management framework for the whole of this vast marine eco-region.

ecosystems, from the coast to international waters, and from the seabed to the surface of the oceans (cf. VII.2).

Linking levels and concepts

The movement towards better forms of management will therefore be guided by the existing forms of governance. It will seek overall coherence between policies, be they sectoral policies, territorial management policies or cross-cutting thematic policies such as research or biodiversity strategies. It applies to the land-sea interface, and extends to the sea itself, according to the needs of the spaces concerned. Moving from land to sea (Fig.), the question of territorial management becomes a question of strategic planning of maritime spaces, for example *via* European integrated maritime policy and its environmental pillar, the Marine Strategy Framework Directive (2008). According to the global understanding, these maritime spaces are composed of marine eco-regions. These themselves make up large marine ecosystems, which are subject to cross-border projects, particularly under the dedicated programme of the Global Environmental Fund (GEF). The 'integrated management of the sea and coast' (an expression from the 2009 *Grenelle de la Mer*) is therefore not a fixed framework, but a multi-level dynamic based on adaptation to change. The types of governance that support it are centred around collective learning.

Maritime spaces and globalization

'The growing economic, diplomatic and ecological importance of maritime spaces in globalization is, more than ever, making the sea a political issue, through which a state can shine and assert its power on the international scene.' These are the words of a recent report from the French Senate on maritimization (2012). In this regard, the example of maritime transport is particularly revealing (cf. V.14). The network of maritime routes connects trading posts or ports, which are the nodal points of these international trade networks. There are dedicated lines, for example from an oil terminal or a nickel mine to specialized terminals near the plants that process these raw materials. Other lines are like motorways (Mediterranean, the Channel-North Sea line...), with a constant stream of all kinds of vessels, connecting production zones to consumption zones. Certain nodal points are multi-functional major ports (Shanghai, Singapore, Rotterdam...), serving both a hinterland and secondary ports *via* river or land transport. It is a living global network, which is constantly evolving as new operating zones and settlement zones emerge. More than ever, we are living in a 'maritime' century, which is of course built upon a long history (that of the Silk Road and the great discoveries), but which is now regulated by an international legal framework and by forms of governance that must be implemented in national waters (exclusive economic zones) and international waters (the common heritage of mankind).

Towards global governance of the oceans

The Convention on the Law of the Sea at Montego Bay was the first international legal arrangement and a true Constitution of the Sea. It is a compromise between the principles of freedom, sovereignty and mankind's common heritage. However, this compromise is proving ill-adapted for today's challenges. It is poorly coordinated with other international regimes developed since the rise of environmental concerns and of new scientific knowledge on biology, climatology, different pollution types, biodiversity protection and risk management. The future global governance of the oceans will need to be based on a set of integrated legal tools and on institutional arrangements leading, for example, to the creation of a World Oceans Organization (WOO).

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3. Ecosystem services of the oceans

Jean-Marc Fromentin

The rapid decline in biodiversity and the legitimate costs of its protection led the scientific community to develop quantitative approaches to assess the full (direct and indirect) benefits of ecosystem services. This type of approach emerged in the late 1970s, but it was the Millennium Ecosystem Assessment coordinated by the United Nations that popularized the concept of 'ecosystem services' (cf. VII.4). The report alerted the international community to the increasing loss of these services and also pointed to the fact that reducing the human impact on ecosystems is not a technical problem or a lack of scientific knowledge, but originates from the fact that the services provided by the ecosystem are considered to be free and unlimited. Since then, the concept of ecosystem services has been central to most national and international biodiversity agreements, including the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES, established in 2012). These services are usually divided into four domains (Fig.).

Support services

These are the services necessary for the production of all other ecosystem services, whose effects are mainly indirect and act in the long term. The ocean is crucial to the water cycle (storage), recycling of nutrients (such as carbon), primary production (mainly planktonic), and as a habitat for many animal and plant species. However, human activities disrupt the ocean's support services. Thus, anthropogenic pollution contributes to the eutrophication of coastal areas (cf. VI.11), the development of toxic plankton and the contamination of the ocean food chain (cf. VI.10). The oceans also support economic activity, including employment, through various procurement or shipping services.

Procurement Services

The products obtained from the ecosystems are of course food, but also energy or minerals. The oceans have always been a source of supply for humanity, first of all through fisheries. More recently, new supply services emerged: *1)* food, such as aquaculture production of shellfish, fish and algae (cf. V.10) *2)* energy, such as offshore extraction of oil and gas, the exploitation of wind, waves and tides (cf. V.7); and *3)* minerals, such as aggregates, polymetallic nodules and hydrothermal sulfides (cf. V.5). However, the main modes of exploitation of wild (fisheries) or livestock (aquaculture) livelihoods are considered to be non-sustainable, and those linked to energy resources are regularly responsible for massive hydrocarbon pollution (*e.g.* the explosion of the Deepwater Horizon platform, cf. VI.13). The evaluation of ecosystem services has made it possible to quantify the cost of these impacts and has thus greatly contributed to awareness of the implications of the deterioration of such services for human development.

Regulatory services

Ecosystems also provide indirect services that are essential to the survival of humanity. The ocean thus plays a key role in climate regulation (cf. II.10). It contains about 50 times more carbon than the atmosphere, with which important exchanges continuously occur. CO_2 sequestration in the Deep Ocean due both to biological processes (CO_2 is captured in the surface layers by the photosynthesis of phytoplankton, then transferred to the base *via* trophic networks and sedimentation) and to physical-

The four domains of oceanic ecosystem services. © E. GODET / J.-M. FROMENTIN. ■

chemical properties (in particular related to the plunging of polar cold water masses). The ocean is also hypothesized to slow the pace of climate change by absorbing nearly a third of CO_2 emissions of anthropogenic origin. Furthermore, microbial loops in the oceans seem to play an important role in the detoxification of a large number of anthropogenic components.

Cultural services

Cultural services encompass the non-material benefits that humankind derives from ecosystems. The ocean is the scene of numerous tourist and recreational activities (boating, swimming, diving, sport fishing...), but also educational (traditional and scientific knowledge), aesthetic (art and design), spiritual and heritage-related (tradition). This notion of cultural ecosystem services is probably the most controversial, in particular because the cultural values attached to the natural environment are based on the uniqueness of a region, a natural environment has strong symbolic meanings, and finally values that do not result from the intrinsic properties of ecosystems, but from a culture.

The notion of ecosystem services has thus contributed to greater awareness of the interdependence of human development with its natural environment. However, this notion has also profound scientific, philosophical or political implications. The academic concept of ecology considers the ecosystem as the place of interactions of living organisms with each other and with their environment. In this approach, human beings are part of the ecosystem, along with other organisms, even if human influence is decisive. The notion of ecosystem services, on the other hand, endorses a much more anthropocentric approach, the advantages of which have been mentioned, but whose risks ultimately validate a purely utilitarian and market representation of nature. The future of IPBES is likely to play a key role in resolving this tension that drives many of today's scientific and societal debates.

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4. Marine Spatial Planning

Marie Bonnin

Unlike the continents, the sea has always been an area of freedom. It has long been possible to exploit and navigate its resources in the absence of pre-established rules. It was only in 1982 that the United Nations Convention on the Law of the Sea, also known as the 'Oceans Constitution', defined the rules applicable in terms of boundaries and the general principles concerning the exploitation of marine resources. At state level, the rules developed were mostly sectoral. Thus, activities such as fisheries or nature conservation have been regulated by separate texts.

The development of offshore activities goes hand in hand with their diversification. Traditional activities have been complemented by new ones that occupy the maritime space. These new activities, such as the development of oil or mining, or the development of renewable energies, have the particularity of being fixed and requiring the establishment of concession zones in order to be sustainable. This diversification of activities at sea also has the effect of multiplying the types of actors involved in the same maritime area, justifying the need to organize activities at sea to reconcile usages.

A cross-sectoral system for sea management

Faced with these new challenges, Marine Spatial Planning (MSP) opens up possibilities of combining the different uses of marine resources in a single space. The MSP was presented by Unesco in 2009 as a process aimed at establishing a more rational use of marine space and interactions between its uses to balance the demand for development with the need to protect the environment within a sustainable development. It makes it possible to organize different activities, such as oil exploitation, fishing, nature conservation, tourism, the development of new forms of energy, within the same space,

Unlike the integrated management of coastal zones promoted by the International Oceanographic Commission and the European Union following the Summit on Sustainable Development and based on environmental approaches, the MSP aims to dedicate a marine space to the realization of activities at sea; it can be translated into a legal zoning document. However, the legal nature

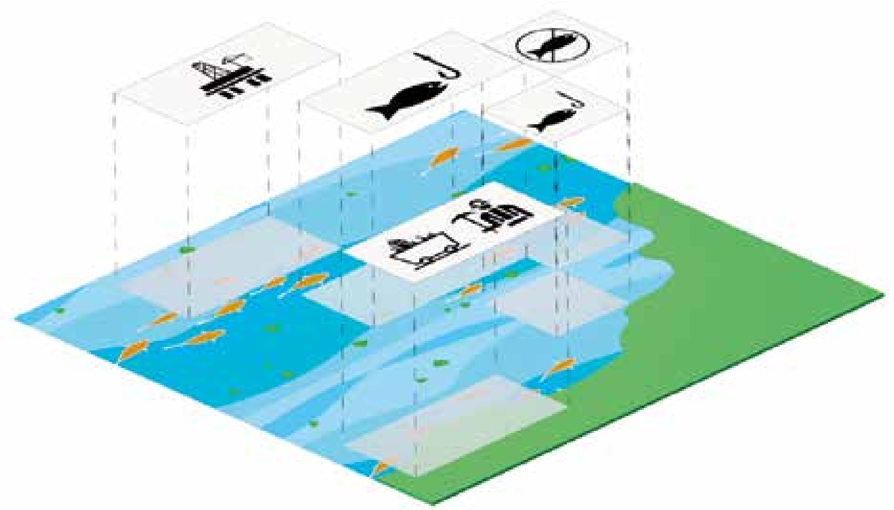

Fig. 1 – **Diagram highlighting the contradiction between zoning of coastal area for several activities and the fluid nature of the ocean.** Project H2020-RISE-PADDLE. ■

Fig. 2 – **The Charter for promoting blue growth adopted by Cape Verde in 2015 highlights the importance of conciliating uses at sea.** © M. BONNIN / IRD. ■

of the planning document is not defined and it is up to each country to adapt the process to the social and political context.

In Europe, European Directive 2014/089 obliges Member States to establish a framework for organizing human activities at sea in order to ensure ecological, economic and social objectives are achieved but without specifying the nature of the legal text that could put the MSP in place. States can therefore either establish binding zoning texts or simple policy strategy documents.

Differentiated objectives

This European directive emphasizes the importance of achieving ecological, economic and social objectives (without prioritizing them), which may involve contradictory policies (Fig. 1). For some scientists, the MSP has its roots in nature conservation, including the Australian example of protecting the Great Barrier Reef. For others, it is essentially designed to reconcile economic activities at sea.

Depending on the actors concerned by the MSP, the objectives are also differentiated. While petroleum companies are primarily concerned with ensuring opportunities for offshore operations, conservation organizations emphasize the importance of conserving natural areas, and fishermen the need to ensure access to areas that are large enough to allow the exploitation of fishery resources (Fig. 2).

Depending on the country where this process is implemented, one or the other of the objectives is prioritized. For example, China and Taiwan have developed binding legal tools to maximize economic opportunities, while others, for instance, the countries bordering the North Sea, seek to reconcile economic development with protection of the marine environment.

A priori, this process is very positive thanks to the conciliation of uses it targets, which implies an interdisciplinary and integrated view of the marine environment. But despite the strength of this view of marine development, many questions remain about the impacts and long-term use of this process. It will be important to analyze the MSP effects on the distribution of resources and competences between States and multinational companies to avoid any risk of appropriation of the sea (dispossession of the traditional rights of local communities, following the modification of access rights relating to the exploitation of marine space or marine resources). Changing access rights to the exploitation of marine resources can lead to the dispossession of the traditional rights of fishing communities in all regions of the world.

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5. Mineral and energy resources

Walter R. Roest and Yves Fouquet

Our planet is currently the sole source of the natural resources needed for human life. Historically, a large proportion of mineral and energy resources was extracted from mainland areas, but it is becoming increasingly difficult to find high-quality, accessible reserves on land. At the same time, global demand for raw materials is increasing, particularly due to population growth. New technologies are being developed, including green technologies, but they consume specific minerals. To diversify and secure supply, a number of countries have therefore embarked on the exploration and exploitation of mineral and energy resources from the seabed and subsoil. Located on the continental shelves surrounding the continents and in deep ocean waters (Fig. 1) and formed over millions of years by geological processes, their exploitation is, by definition, not sustainable, and we will need to find a responsible way of using them.

Location of and jurisdiction over natural resources

There is a long history of near-shore exploitation of seabed natural resources (oil, marine aggregates, gold, and diamonds). More recently, developments in technology and the improvement in our geological understanding of the seabed have made it technically possible to exploit resources at depths of several thousand meters and at distances of hundreds and even thousands of kilometers from the shore. The economic viability of such exploitation, though, will depend on the price of raw materials. Canadian mining company Nautilus Minerals recently announced that the first undersea mine, located off Papua New Guinea at a depth of around 1,800 m, will begin extracting copper, zinc, and gold in 2019.

The issue of the use of physical resources from the seabed and subsoil is also linked directly to the question of ocean governance (cf. VII.3). The United Nations Convention on the Law of the Sea grants coastal countries jurisdiction over any exploitation of these resources in the Exclusive Economic Zone up to a distance of 200 nautical miles from the shore and, on the continental shelf beyond this distance, on the submerged natural prolongation of the country's land mass. Beyond a country's continental shelf, the Convention assigns the management of seabed and subsoil resources to the International Seabed Authority, on behalf of the entire human community.

Mineral and energy resources

Nodules are 5-10 cm-diameter lumps consisting of manganese and iron hydroxides containing 40% water. They are formed, at depths

Fig. 1 – Types of deep water mineralization: nodules, crusts and hydrothermal sulfides. © Y. FOUQUET / Ifremer. ■

of more than 4,000 meters in low-sedimentation areas, from metal complexes dissolved in seawater or present in the sediment. Worldwide, the Clarion-Clipperton zone in the North-East Pacific has the richest deposits of copper (0.82%) and nickel (1.28%). It also harbors minor metals (cerium, zirconium, molybdenum, lithium...) and rare earth elements.

Iron-manganese crusts are found in all the oceans in hard-substrate environments with very low sedimentation rates. They vary in thickness from a few centimeters to 25 cm and grow extremely slowly, from 1 to 6 millimeters over millions of years. Estimates show that an area of 6.35 million km² of the ocean floor (or 1.7%) is covered with crusts. The cobalt- and platinum-rich deposits of economic interest are situated in the Pacific Ocean, at a depth of between 800 and 2,500 meters, and consist of iron and manganese oxides and a number of minor metals.

Hydrothermal sulfides are the result of seawater circulating in the ocean crust. Sulfide mineralization has been found at depths of between 800 and 5,000 m in the main geodynamic environments (slow- and fast-spreading ridges, back-arc basins, and island-arcs) and on a variety of substrates (basalt, andesite, dacite, sediment and the ultramafic rocks of the mantle). Depending on the environment and the nature of the substrate, mineralization may have high concentrations of copper, zinc, silver, gold..., as well as rarer metals (selenium, gallium, germanium, mercury...).

The exploitation of oil and gas – the traditional sources of energy – takes place the world over on the continental shelves, at depths of up to 3,000 m and up to 10 km beneath the ocean floor. Offshore oil today accounts for 30% of worldwide oil production (Fig. 2). The gas hydrates (cf. V.6) discovered more recently could provide energy resource for the future. These are molecules of gas (like methane) surrounded by a 'cage' of water molecules, with the appearance and consistency of ice. A given volume of hydrates can release 160 times that volume of methane as it decomposes. However, use of this resource requires cutting-edge technology developments. Destabilizing the vast swathes of gas hydrates found on the continental shelves could have a catastrophic impact on the stability of continental slopes, and a proportion of the greenhouse gas that this would release could reach the atmosphere and impact the climate.

Fig. 2 – **Full view of the Tension Leg Platform, Moho Nord Project, Total subsidiary E&P Congo. © D. MALFERE / TOTAL.** ■

Environmental impact

The technologies for exploiting the ocean's physical resources are developing rapidly. In contrast, the study of the impact of exploration and exploitation on biodiversity and deep-water ecosystem functioning is at a very early stage. Marine biologists have sounded a warning that there must be no repeat at sea of the errors committed on land, and the precautionary principle should, therefore, be applied to all exploration. Extensive use of deep sea mineral and energy resources will not emerge overnight, but the multidisciplinary advances in science may, one day, mean they can be exploited responsibly for the benefit of all humanity.

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6. Is It feasible to mine natural gas hydrates?

Nabil Sultan and Livio Ruffine

Gas hydrate has the appearance and consistency of ice. It is made up of cage of water molecules in which gas molecules such as methane are trapped. In nature, hydrates mainly contain methane and are stable under low-temperature and high-pressure conditions. They have the particularity of concentrating a large quantity of gas. Such temperature and pressure conditions are found in permafrost regions and at the bottom of the oceans, at depths of more than a few hundred metres (Fig. 1). The gas contained in these gas hydrates is generally the result of microbial alteration of the organic matter contained in the shallow sediments. Occasionally, this gas can be of thermogenic origin and come from deep hydrocarbon reservoirs.

Under standard pressure and temperature conditions, a unit volume of hydrates can store (or release), around 160 volumes of methane during its formation (or its decomposition). This characteristic earns it the name 'burning ice', because upon decomposition it releases hydrocarbons which burn in contact with a spark (Fig. 2). For this reason, hydrates are as much a source of expectation for their potential contribution to energy supply as they are a source of fear for the climate disturbances and hazards they may cause.

Generally, the exploration and evaluation of gas hydrate accumulations are inferred from seismic data. Nevertheless, these data can be confirmed using borehole data. The current estimate of the quantity of methane (20.106 km^3, according to the American Geological Survey – USGS) is constantly being re-evaluated. This highlights the need to compare indirect measurements against field observations, which are still too limited.

The geological and climate risks

Rising water temperatures and/or falling sea levels may destabilize hydrates and cause methane to be released. This generates high fluid pressures in the sedimentary column, which in some cases exceed the fracture pressure, and

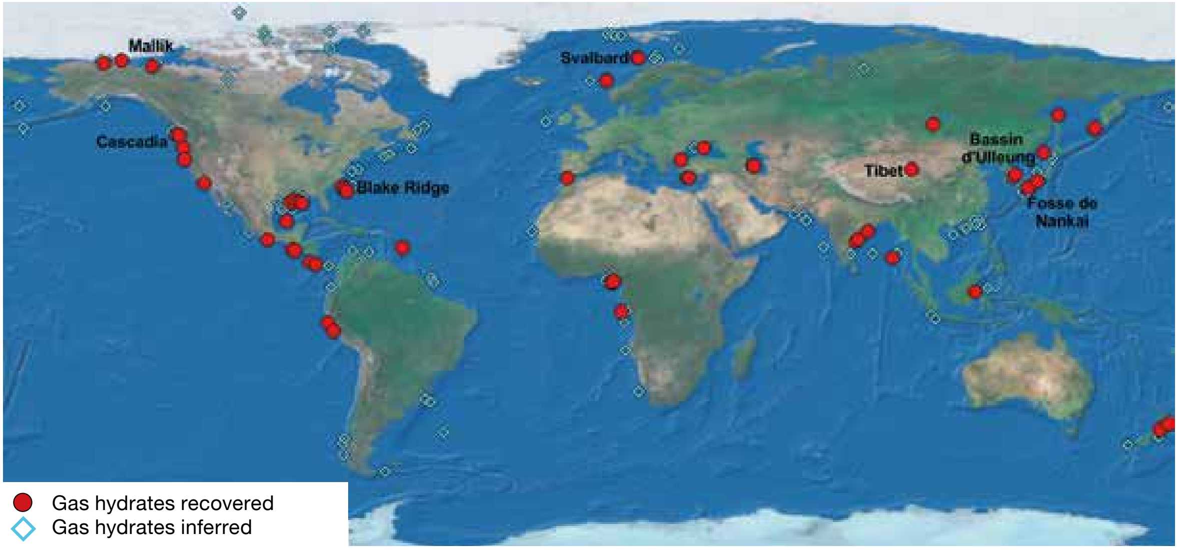

Fig. 1 – **Map showing the distribution of gas hydrates.** Source: U.S. Geological Survey. ■

create preferential conduits between the hydrate reservoirs and the ocean floor. This excess pressure can weaken the sediment and, in certain conditions, cause sedimentary deformations which can lead to submarine landslides.

Methane is also a powerful greenhouse gas, and its diffusion to the atmosphere, following a massive and global decomposition of gas hydrates (adverse climatic period), can contribute to an increase in the global temperature and therefore to an amplification in the hydrate decomposition process. Some researchers believe that this catastrophic cycle was the underlying cause of climate upheavals in the past, and we cannot dismiss the possibility of its recurring.

A potential energy source

Gas hydrates are the largest methane reservoirs on the continental margins. Consequently, some countries (Japan, South Korea, India, Canada...) see them as a new source of carbon energy. Four methods for extracting this gas are currently under investigation: depressurization, thermal stimulation, chemical inhibitor injection, and a combination of the three. The injection of CO_2 is a special variant of inhibitor injection, because it is thought to offer the advantage of helping resolve two of major challenges in society today: supplying energy and reducing CO_2 emissions. For these different methods, the aim is to induce the decomposition of the hydrates, by transforming them into free gas and water, so that this gas can then be collected at the surface. However, in recent years, two production experiments (in Alaska's permafrost and the Nankai Trough off the south-west coast of Japan) have been halted prematurely because of geo-mechanical problems.

Fig. 2 – **Burning ice.** © Ifremer. ■

Research themes to be developed

The current state of knowledge on natural gas hydrates does not allow us to develop a reliable technology for methane extraction, or to provide a consensual response to the geological hazards and climate threats. There are numerous grey areas, and the approaches preferred by the geosciences community today encompass: *i)* improving the detection and quantification of gas hydrates; *ii)* carrying out in-depth study of the dynamics and stability of gas hydrates; and *iii)* characterizing the mechanical properties of gas hydrate-rich sediments and their evolution over time, from their initial state to their decomposition. Better detection and quantification of gas hydrate concentrations in sediment layers and frozen ground is the first key to a quantitative analysis of this supposed connection between gas hydrates and climate and geological hazards, but also to this supposed treasure trove of energy resources. Better characterization of the thermodynamic stability of gas hydrates and its interactions with the sediment matrix will lead to improved evaluation of the consequences of global or anthropic changes on gas hydrates. The two recent examples of production tests (Alaska and Nankai) have shown the formerly underestimated complexity of the mechanical behaviour of gas hydrate-rich sediments. It now seems crucial to take this into consideration, through experimental and theoretical characterization.

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7. Marine renewable energies

Bernadette Mérenne-Schoumaker

In 2015, marine renewable energies (MREs) accounted for 0.8% of global renewable electricity production, which itself represents 23.7% of global electricity production. This is a tiny fraction, when the seas and oceans cover 70% of the Earth's surface. However, with the exception of tidal energy, marine energies are a recent power source, because the first offshore wind turbine was installed in 1991 in Vindeby (Denmark) and the first offshore wind farms only date back to the early 2000s. In this short period, there have been many advances, although the situation varies between resources (Fig. 1).

Tidal energy

Tidal energy has been used on a small scale since the 11th century, in the form of tidal mills on the Atlantic coasts of France, Spain and Great Britain. Its usage on an industrial scale started in France in 1966, when the Rance tidal power station (240 MW) began operating near to Saint-Malo. There are a few small power stations in Canada, China and Russia, but only one other large station on Sihwa Lake (254 MW) in South Korea, operational since August 2011. Tidal power clearly has significant potential in the world (around a tenth of global hydroelectricity production). However, the installation conditions are quite restrictive in terms of tidal ranges, the configuration of the site, ecological constraints, and high investment and maintenance costs. Several projects exist, particularly in Canada and the United Kingdom, including Swansea Lagoon (240 MW) with the construction of an artificial lagoon in Swansea Bay.

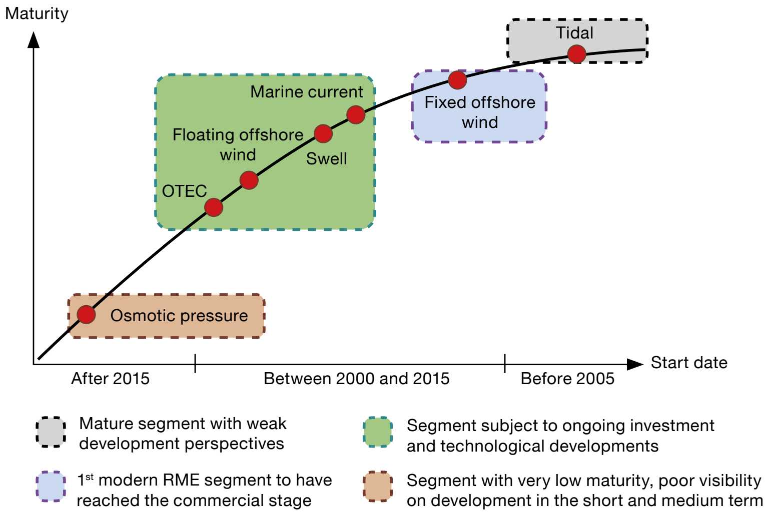

Fig. 1 – **Maturity of marine energies.** Source: France Energies Marines. ■

Offshore wind power

This technology displays much more spectacular growth. Today, there are 3589 'fixed' wind turbines across 81 offshore wind farms (Fig. 2). The total production capacity is 12,631 MW, compared to just 801 MW in 2006. The United Kingdom is the European leader, followed by Denmark, Germany, the Netherlands and Belgium. Despite its significant potential, France has been slower to start using offshore wind power, but 3 GW are due to be installed from 2020. Offshore wind power presents many advantages compared to onshore wind power: stronger and more regular winds; less usage conflicts due to the distance from the coast; a better capacity factor and consequently less recourse to power plants for back-up; and half the CO_2 production for the same wind energy yield. However, suitable sites for wind turbines are rarer, and above all the projects are more expensive so require funding from the public authorities. Moreover, to install wind turbines at depths of over 50 m, on continental plates, the turbines need to be mounted on floating structures. This floating offshore wind turbine technology is currently at the demonstration stage in several countries.

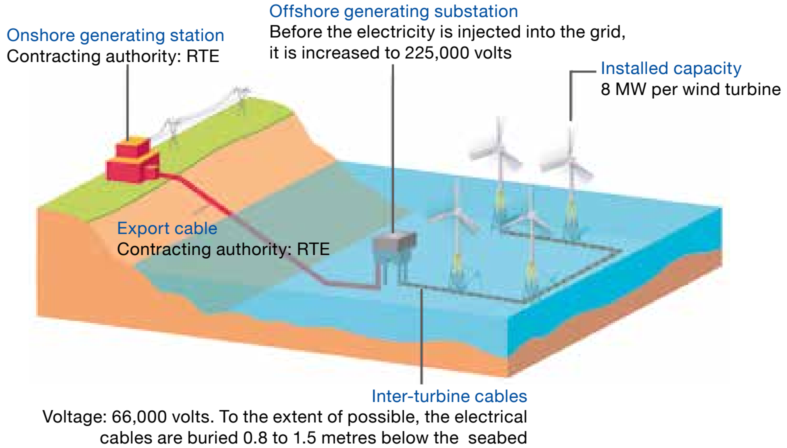

Fig. 2 – **Example of the operation of an offshore wind farm, with ADWEN's AD8-180 wind turbine for the project in the Bay of Saint Brieuc.** Source: www.eolienoffshoresaintbrieuc.com. ■

Marine current turbines

Much smaller than wind turbines, but offering the same power (because water is about 800 times denser than air), marine turbines are driven by marine currents. They can be placed horizontally or vertically beneath the surface of the water, or on the seabed. They offer the advantages of predictability (with quite a high capacity factor of around 50%), low impact on the marine environment, and less exposure to the sea's variations. However, they can only be installed on sites where the currents move faster than 1.5 m/s. This means that installation and maintenance costs are rather high, particularly because of salt corrosion and damage by micro-organisms. These marine turbines must also share the waters with other maritime activities, such as fishing, shipping and water sports. Today, there are only around 30 marine turbine demonstration units in the world. Two of these are in France, at Paimpol-Bréhat and off Ushant Island. In 2014, on a global scale, the IRENA (International Renewable Energy Agency) forecast an installed capacity of 200 MW from marine current turbines by 2020.

Other sources of marine energy

Other ways to convert energy from the seas and oceans into electricity are currently being explored. These include: ocean thermal energy, which exploits the temperature difference between the oceans' surface waters and deep waters, using the same principle as geothermal energy; wave and swell energy, *via* wave energy installations that look like long, floating sea snakes; osmotic energy, which uses the osmosis phenomenon between fresh and salt water, for example around estuaries, to generate a pressure difference and turn a turbine; and marine biomass, which uses algae and phytoplankton through gasification, fermentation or combustion.

For the future, RMEs face three major challenges. The first is limiting the impacts on often very fragile natural environments: noise and vibrations, changes to the habitat of underwater flora and fauna, and barrier effects for bird migration. Conflicts with other users of the sea must also be avoided, and above all, we need to make RMEs competitive by reducing the production cost of offshore wind power (twice as high as onshore wind power at around €80/MWh) and that of tidal energy (three times higher). Therefore, we need to reduce not only investment costs, but above all maintenance costs (often 20% of the total) by anticipating and avoiding risks. This will allow us to minimize the number of sea trips and schedule them for the most appropriate times.

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8. Toward responsible and sustainable fisheries

Jacques Bertrand

Fishing is a human activity that has been practiced since the Paleolithic era (about 40 000 years ago) and which still represents a major food, nutrition, income or livelihood resource (FAO 2016). Global production of offshore fisheries has increased steadily since the 1950s, to quadruple in the mid-1990s (Fig. 1). Since then, production has remained stable at about 80 million tons per year.

Worldwide Production

The Pacific Northwest area is the most productive fishing area, followed by the Central West Pacific, the Northeast Atlantic and the East Indian Ocean (Fig. 2). With the exception of the Northeast Atlantic, these areas have enabled an increase in catches in recent years compared to the average for the period from 2003 to 2012. In contrast, in the Mediterranean and the Black Sea, catches of many species dropped by one third since 2007, mainly those of small pelagics such as anchovy and sardine.

The ten most productive species alone account for one quarter of the world's catches. The Alaskan pollock was top in 2014, with 3.2 million tons, followed by small pelagic fish (anchovies, sardinella, mackerel, and herring) and tuna (skipjack and yellowfin tuna). At the species level, production is subject to significant inter-annual variations. For example, with an output of 2.3 million tons in 2014, Peru's anchovy catches were halved compared to 2013, but reached more than 3.5 million tons in 2015. At the global scale, 2014 witnessed record levels of production for groups of high value species such as tuna, lobster, shrimp and cephalopods.

Since the stabilization of catch fisheries, the expansion of aquaculture has led to a very large increase in the supply of fish for human consumption, from 7% of the total supply in 1974 to more than 50% in 2014. Thus, the global supply of fish for human consumption has grown faster than the population, which has led to the doubling of apparent per capita fish consumption since the 1960s (from about 9.9 kg in 1960 to 20 kg in 2014-2015, of which 26.8 kg in industrialized countries).

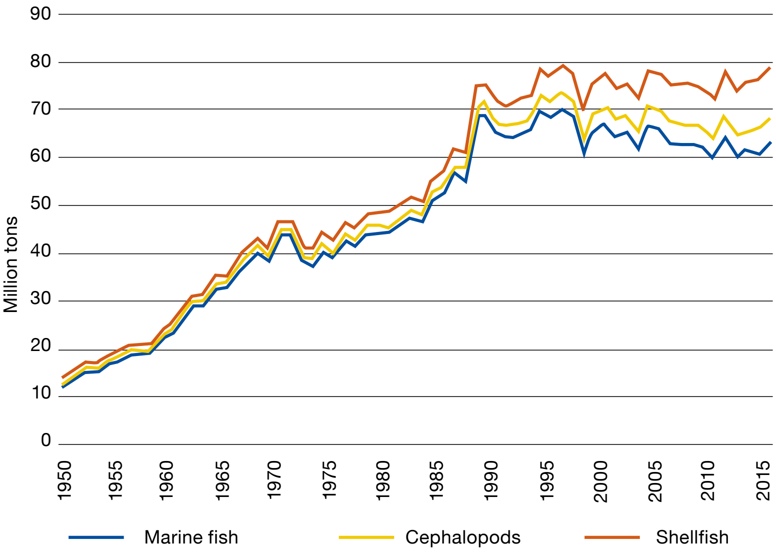

Fig. 1 – **Increase in world fisheries production since 1950.** Cumulative data, source: FAO. ■

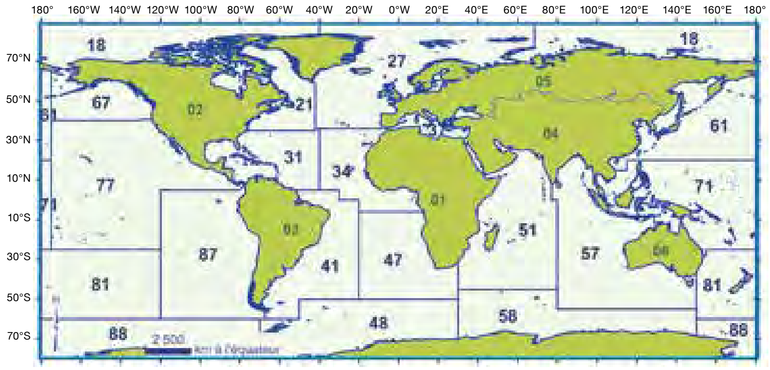

Fig. 2 – **Areas defined by the FAO for the purpose of world fishery statistics and used to identify the origin of catches of fishery products.** ■

Stock status

Despite significant progress in some areas, the condition of fish stocks has not improved in recent years. According to a study by the FAO (Food and Agriculture Organization of the United Nations), while the proportion of assessed stocks exploited at a biologically sustainable level was 90% in 1974, it was only 68.6% in 2013. The proportion of under-exploited stocks decreased almost continuously between 1974 and 2013, but that of the maximum exploited stocks, after plummeting from 1974 to 1989, rose to 58% in 2013. At the same time, the study showed that the percentage of stocks exploited at a biologically unsustainable level increased, particularly in the late 1970s and 1980s, from 10% in 1974 to 26% in 1989. Since 1990, these stocks continued to increase, although at a slower pace, up to 31.4% in 2013.

This situation reveals marked heterogeneities across the oceans. Thus, the proportion of overexploited stocks is highest in the eastern Atlantic, the Mediterranean and the Black Sea (about 50%), and lowest in the northeastern Pacific (0%).

In fisheries management, a level of exploitation is considered to be biologically sustainable if it is possible to maintain a maximum constant yield of the stock concerned over the years. Above the maximum sustainable yield threshold (MSY), the stock is considered to be overexploited. As a management objective, this means maintaining fishing mortality below the level defined by this threshold.

Sustainable development of fisheries

There are many challenges to the sustainable development of fisheries. They are defined according to the three dimensions inherent in this concept: economic, ecological and societal. They focus on food security and nutrition, fish being one of the most important sources of animal protein. They create a need to maintain the balance between ecosystems of interest to fisheries, which involves the fight against pollution in all its forms and the preservation of marine habitats. They involve reversing overexploitation trends, including combating illegal fishing, currently estimated at 15% of total fisheries production, and developing fisheries management plans to adjust fishing pressure to the renewal of resources. Finally, they also concern economic and societal aspects. For the FAO, the goal is to promote viable, shared and sustainable economic growth, as well as full and productive employment and decent work for the 56.6 million people who were working in primary fisheries and the aquaculture sector in 2014.

The combination of all these points of view supports the development of integrated maritime policies implemented from local level to that of the wider marine ecosystems, implying the coordination of governance of between the sectors concerned.

One way of achieving sustainability introduced by the Code of Conduct for Responsible Fisheries (FAO 1995), is making all the players accountable, through awareness raising and information about the products and their value chain (guides, eco-labels and certification schemes), in particular using markets as a lever to move toward sustainability-related practices.

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9. Artisanal fisheries in the context of sea globalization

Marie-Christine Cormier-Salem

Artisanal fisheries is a key sector of the economy, particularly for neighboring countries around the Mediterranean Sea and in the intertropical zone, which according to the FAO, employ 90% of the sector's workforce. Artisanal fisheries contribute significantly to food security and poverty reduction. In Africa and Asia, more than 50% of animal protein is supplied by fish. Artisanal fisheries are organized around a rich natural and cultural heritage, yet find themselves in danger, due to the globalization of exploitation, trade, and fisheries management policies.

A wide range of marine professionals are concerned not only by artisanal fisheries but also by other forms of exploitation of fishery resources (shellfish harvesting, marine farming...). This world, which is dominated by men, should not underestimate the role of women. While in many countries (notably the Pacific), women are prohibited from embarking, at least 20% of those directly involved in fishing activities are women and their role is predominant in the seafood value chains (processing, distribution, consumption).

Different sustainability issues

Given the diversity of actors, exploitation techniques, and contexts, the ecological, socio-cultural and economic stakes are highly contrasted, and three aspects are subject to controversies. First, artisanal fishers are seen as predators, exerting anarchic and unsustainable pressure on resources, held responsible for the erosion of marine biodiversity. It is certain that since the 1950s, particularly in southern countries, the sector has undergone a phenomenal explosion, with a tenfold increase in catches between 1950 and 1995, an increase in regional and international demand and trade, an amplification of migratory movements, as well as an extension of fishing territories. Growth is such that from the 1990s on, scientists, relayed by NGOs, have begun denouncing the plundering of the sea, leading to changes in public policies. The

A rich and diversified world (with economic, social, nutritional implications). Left: Xuan Thuy landing in Vietnam. Right: Mbour landing in Senegal. © M.-C. CORMIER-SALEM. ■

development of fishery targeting shark fins, and fueling the Southeast Asian market, is a good illustration of the consequences of overfishing. This practice, from Mauritania to Madagascar and throughout Asia, is often carried out by young opportunistic fisher units. Many ethnographic studies show that the sea and its resources are not free of access, but rather common goods, collectively controlled by artisanal fishing communities, through traditional institutions, and that privatization or coercive public measures may lead to the decline or even disappearance of these communities. Another premise is that artisanal fishers are marginal and poor populations, poorly equipped to withstand competition, particularly from industrial fishing, and are confronted with many conflicts. The sea was long considered as an empty – and dangerous – territory, on which communities turned their backs. Only minority and dominated populations would have been forced to take refuge there.

While it is necessary to denounce the determinism and the historicity of such attitudes, the fact remains that, for a long time, sea peoples formed a world apart, on the fringes of continents, neglected and unknown, and there is an acute lack of data concerning them. What we do know, however, is that their health is better than that of hinterland farmers, notably because of the availability of many resources, which formed the basis of a diet rich in animal proteins and salt, and their location at the land-sea interface, which encouraged trade. Furthermore, many stories and media spotlight the qualities of proud, hard-working people who have the courage to face the sea, to such an extent that marine safety programs are often hard to implement, since wearing a life jacket tends to undermine a fisherman's virility. The complexity of fishing systems is reflected in the diversity of socio-professional status. The asymmetry of resources between artisanal and industrial fisheries is obvious in EEZs subject to the regulation of fishing effort; the conflicts are real, due to the lack of sufficient control by the fisheries administration. Yet, it is also worth noting the frequent arrangements reached in Africa where artisanal fishermen's pirogues are towed by trawlers because they are able to access bedrocks rich in demersal species, and their catches supply industrial fisheries.

A third controversy concerns the predicted disappearance of these activities in the face of climate change, the urbanization and concreting of the coastline, the commodification of nature, neoliberalism and the globalization of governance of the sea, including the signing of unequitable fishing agreements, to the detriment of communities of artisanal fishers. While there is reason to question the environmental and social vulnerability of coastal communities, their innovative and organizational capacities should be underlined, as evidenced by the consolidation of fisheries workers groups, made up of both men and women from 33 countries who, since 1997, have been organizing a world day (November 21) as well as running a global forum.

Towards sustainable local alternatives

Artisanal fisheries are now on the agenda of national and international policies, from blue carbon, blue wefts, to the blue economy. How can artisanal fishers contribute to the preservation of biodiversity and ecosystem services? Lessons can be learnt from the initiatives taken by these communities, both in the development of local conventions on fishing territories and in the recognition of Autochthonous and Community Heritage Areas (ACAC), which contribute to the reflection on nature-based solutions, in the field of heritage building and ecotourism development and, more broadly, maritime heritage, or the promotion of seafood products through labels such OVOP "One Village, One product" , initiated almost 40 years ago in a Japanese fishing village.

The main challenge is the implementation of conservation and valorization measures for marine biodiversity, in other words, ensuring the effectiveness of co-management, and the participation of sea peoples in the government of their territory.

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10. The major challenges of aquaculture

Chantal Cahu

Aquaculture is an increasing way of resorting to the ocean. While the specialized literature describes mullet farming in the Venetian 'valli da pesca' (marsh) as dating from more than 1000 years ago, the intensification of this activity is very recent. In 1970, less than two million tons of fish and other animal species were produced by marine and inland aquaculture, in 2014, this figure had reached 74 MT. In addition, aquatic plants, mainly macro-algae, accounted for 27 MT, along with the cultivation of microalgae that has been expanding in recent years. This adds up to the 93 MT of fish caught (fishing), together representing a resource of 194 MT. Aquaculture thus contributes extensively to the food security of populations, and aquaculture, like fisheries, appears to be in line with sustainable development goals. In addition, it mainly developed in emerging countries in South Asia and in some African countries, with China accounting for almost two-thirds of total production.

The species concerned

In 2016, the FAO (Food and Agriculture Organization) collected production statistics on more than 500 aquatic species farmed across the world. Inland aquaculture, which accounts for 47 MT, mainly produces herbivorous or detritivorous fish such as carp, tilapia, or catfish. Marine aquaculture mainly refers to seaweed farming and in 2014 27 MT of wakame (sea fern), Euchema or laminaria (algae) were produced for the food, pharmacological and cosmetic industries. Marine aquaculture also produces 16 MT of molluscs per year (Pacific oysters, clams, mussels), 6 MT of fish (salmon, sea bass, halibut, sea bream, turbot, and amberjacks) 4 MT of shrimp; other species (sea cucumbers, sea urchins or jellyfish) representing 0.5 MT.

Unlike in the terrestrial environment, the wide range of species is due to the initiatives of the coastal populations who raise local species for food. Its success is also due to work carried out in research laboratories. The life cycle of marine species, and in particular

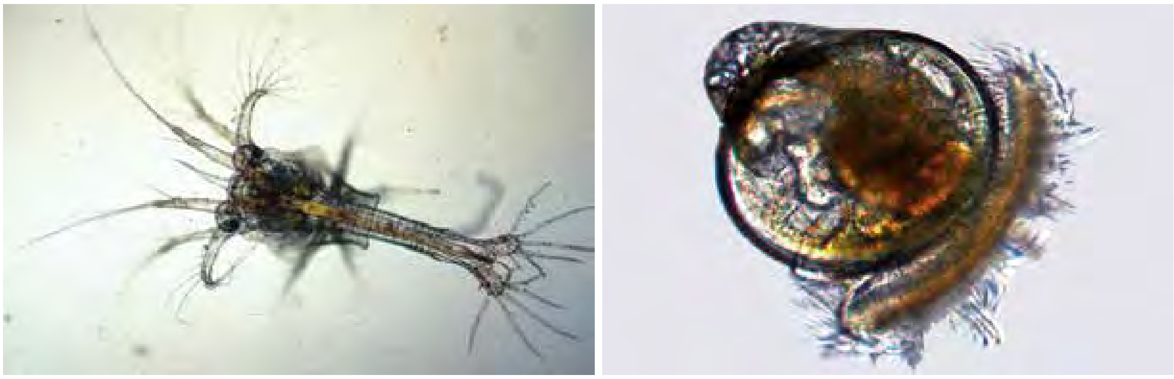

Fig. 1 – On the left: Penaeid shrimp 3 days after hatching (5 mm long); on the right: 20-day veliger oyster larva (0.3 mm). ■

of invertebrates, is very complex and the knowledge acquired during the domestication of terrestrial animals is not easy to transpose. For example, at hatching, a mollusc or shrimp larva weighs a few milligrams, with a barely sketched digestive tract and nervous system, and goes through many metamorphoses before reaching juvenile status. Research in reproductive biology, behavior, physiology, nutrition, immunology, genetics and genomics has produced valuable knowledge that can be applied in aquaculture but also used for the protection of biodiversity.

Fig. 2 – **Traditional fish farming cages in Thailand.** © Ifremer / O. BARBAROUX. ■

Modes of production

Two categories are usually distinguished among species produced in aquaculture. "Unfed" species, which in the marine environment are algae, filtering molluscs, sea cucumbers, jellyfish and sea urchins. These species find the nutrients they need, including mineral salts, microalgae and bacteria, in the body of water or possibly in the sediment. 'Fed' species, which includes most fish currently bred in the marine environment, and shrimp, require feed based on vegetable meal, fish meal, and fish oil. They thus compete, as do other farmed animal species, with food for human consumption. Some of the small pelagic fish and krill (small cold water shrimp) fished (21 MT in 2014) are used for animal feed, including aquaculture. Laboratory research is increasing with the aim of replacing fishmeal destined for aquaculture with meal of plant origin, and particularly with co-products made from insects and microalgae grown in enormous quantities.

Conflicts in use

Breeding techniques are varied and need to take different constraints into account. Whereas French oyster culture in coastal lagoons is part of French cultural heritage, the development of new coastal activities may result in conflicts in uses. Large areas, more than one million hectares worldwide, mainly in Asia and Latin America, have been 'requisitioned' for shrimp, fish and sea cucumber farming. The establishment of earthen basins fed by marine or brackish water, was achieved at the expense of mangroves, and led to ecological problems including the salinization of groundwater. Some countries, for example India, have had to regulate the conditions for the development of this activity. Fish can also grow in cages and offshore cage techniques may help limit the environmental impacts of organic waste of fish. Coupled with wind turbines, this technique appears to be a possible way of developing sustainable aquaculture.

The FAO expects production to increase by close to 35% by 2025, which should help meet the food needs of the growing world population. This objective can be reached provided practices are used that minimize the ecological impact of aquaculture: the use of co-products for feeding fish, diversification of livestock systems, including integrated multi-trophic aquaculture systems that treat organic waste, low-energy or renewable energy infrastructure.

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11. Genetic resources of aquaculture species

Sylvie Lapègue and Béatrice Chatain

Aquatic food production has shifted from focusing on the catching wild fish to the farming of an increasing number of species (Fig. 1). An important milestone was reached in 2014 when the contribution of the aquaculture sector to the supply of fish for human consumption surpassed that of the fisheries sector (FAO, 2016) for the first time. In 2014, out of 74 million tons of aquatic animals produced, 44 million came from inland fish farming, 23 million from shellfish and 6 million from marine and coastal fish farming (cf. V.10).

Farm, domesticate and select

Farming means domesticating, but unlike terrestrial plants and animals (domesticated from the Neolithic on), the process of domestication of aquatic species is very recent: the late 19th century for fish and molluscs (Fig. 2). However, to domesticate is to select, because domestication covers all the genetic modifications inherent in the choice of breeders during the renewal of generations. Character selection is crucial because selection is a long-term process that is expressed over generations, and genetic selection programs have a cost that has to be justified by the expected gains. It is therefore important that the guidelines are well thought out and that priority be given to the efficiency of production systems.

Methods such as life-cycle analysis can help design aquaculture breeding programs that balance productivity with environmental sustainability. Thus, efficiency characteristics such as food efficiency, disease resistance or cutting yields are more economically and environmentally beneficial than purely quantitative ones, such as growth. In this context, the most obvious example is undoubtedly the improvement in livestock health, as in all livestock sectors, the development and intensification of production is accompanied by increasing pressure from pathogenic organisms and an increase in the frequency and/or severity of infectious episodes. Another important characteristic of aquaculture development is the possible control of the sex ratio (ratio of the number of males and females within the same species) in fish and molluscs. Indeed, it allows the implementation of rational breeding programs (control of the proportion of the two sexes for reproduction) or the production of unisex populations (the one of greatest interest to the breeder). The latter technique is often applied to salmonids and tilapias, fish with differential growth between the sexes at the beginning of sexual maturation.

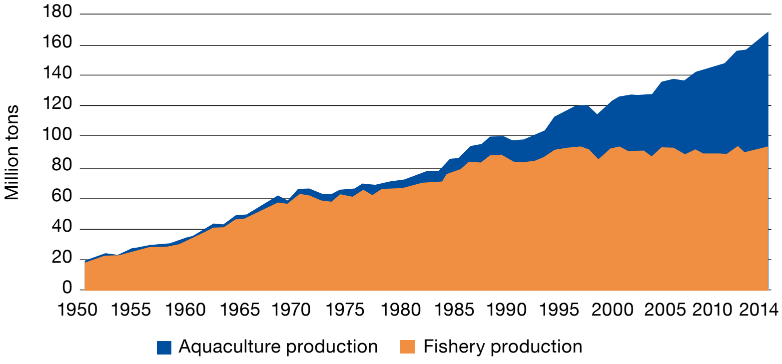

Fig. 1 – **Comparative evolution of fisheries and aquaculture productions in the world.** FAO, 2016. ■

Fig. 2 – **Oyster-culture activity in the Marennes-Oleron basin. © Ifremer / J. PROU.** ■

example, triploid animals that possess two batches of chromosomes of one of their parents and one of the other, and which are generally sterile. The production of such animals has been a major achievement in the development of the shellfish farming industry over the last 30 years. Beyond their economic interest (limited investment in reproduction and increased growth, and widening of marketing options in summer months), they are a tool of interest in limiting interactions between wild and aquacultured populations.

Natural genetic variability at the service of selection

By selecting animals according to their needs, humans only accelerate and orient the natural selection phenomenon, itself based on the exploitation of a genetic variability theoretically almost inexhaustible in the case of the oceans. French oyster farming is an exemplary case of exploitation of the specific variability of resistance to pathogens, this activity having experienced two major pathological episodes leading to the successive exploitation of three different species over a hundred years. Another source of variability lies in the existence of natural populations or livestock populations, mostly of different geographical origins, which have been genetically isolated for a sufficient number of generations to allow the emergence of distinct characteristics. The exploitation of natural resistances can thus make it possible to select animals that are more resistant to the various aggressions encountered in aquaculture farms, as is the case for the resistance to nodavirosis (viral nervous necrosis) in bass. The prerequisite for such a strategy is the existence of genetic variability for the involved traits, as the nature and extent of this variability determines the potential margin for progress.

For cohabitation of breeding and wild populations

Cytogenetics is another discipline used in aquaculture to generate polyploidy, *i.e.* animals whose chromosomal heritage is above normal. This phenomenon, observed in nature in many species, can also be induced to produce, for

The new tools

The development of genetic markers and better knowledge of the genomes of many aquaculture species will enable the development of these tools as support for breeding programs in the years to come, both in the management of stocks and their diversity, and in direct selection assistance in the form of marker-assisted selection or genomic selection. Transgenesis (introduction of foreign genes) has been tested in fish since the early 1990s, mainly to stimulate growth. Due to limited productive interest, the difficulty involved in avoiding escapes in an open environment and strong consumer reticence, no transgenic fish have been marketed to date.

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12. Marine resources and biotechnology

Sylvia Colliec-Jouault

The diversity of the marine resource, closely linked to that of marine ecosystems, represents a vast field of investigation for biotechnology. This discipline is devoted to the search for new processes and new techniques from a bioresource, for the development of applications in the agro-food, chemical, but also cosmetic and pharmaceutical industries. Marine bio-resources, which may be of animal or plant origin, are extremely varied (Fig. 1), as they include fishery co-products (of fish, cephalopods, crustaceans co-products...); invertebrates (worms, sea cucumbers, sea urchins, corals, starfish...); macro-algae (laminaria, gelidium, ulva...), but also micro-organisms, such as micro-algae, bacteria and fungi. Some products from this marine biomass are already marketed as gelling agents, enzymes, moisturizers, vermifuges, antivirals, anti-inflammatories, medical dressings, implants, and so on.

Research underway for several years on very particular or atypical marine ecosystems has enabled the discovery of new animal and microbial species. These were discovered in sediments, water columns, the deep environment, deep hydrothermal springs, high salinity water ponds in Polynesian atolls where microbial carpets called ‘kopara’ developed, New Caledonian biotopes, the Antarctic, Arctic, Indian, Pacific, Atlantic oceans, and also tropical or temperate seas. These newly discovered marine organisms are sometimes very different from continental organisms, and their exploitation will require the development of specific pressure or high temperature-related techniques, and will lead to the production of original molecules. For example, archaebacteria, bacteria and eukaryotes develop in extreme environments (high pressure, high temperature, hypoxia, presence of metals...), in which they produce thermostable enzymes, biologically active secondary metabolites and biopolymers that are not produced by continental organisms. Another example is marine micro-algae, which are capable of producing large quantities of the long polyunsaturated fatty acids known as omega3.

Fig. 1 – **Two examples of marine ecosystem diversity and marine resources.** a) The collection of brown algae (seaweed) in the ‘Scoobydoo’ vessel in the Iroise Sea. © Ifremer / O.BARBAROUX. b) Hydrothermal site: active black smokers in the East Pacific Ocean. © Ifremer. ■

From macro- to micro-resources

Marine macro-resources are currently widely exploited to produce hydrocolloids with gelling or thickening properties, such as alginates, agars and carrageenans. However, the exploitation of macro-resources is affected by problems of physical access to certain habitats, seasonal variations and climatic, ecological and political hazards. Micro-organisms, such as fungi, micro-algae, cyanobacteria and bacteria, have many advantages over macro-resources: they can be produced under fully controlled culture conditions compatible with current safety standards (traceability, containment); different molecules can be produced by the same strain; reproducibility; control of cropping conditions to optimize production… Production is much more rapid (a few days for micro-algae and less than 60 hours for bacteria) and is very profitable (completely automated, high capacity culture systems *e.g.* photo-bioreactors and fermenters already exist). Finally, the extraction and purification of molecules is often simpler than the extraction of molecules from higher plants or animal organs.

Heteropoly-saccharides	Bacteria	Biological Applications
Alginic acid or alginate	*Azotobacter sp.* *Pseudomonas sp.*	Tissue engineering: dressings, biomaterials, encapsulation
Hyaluronic acid or hyaluronan	*Streptococcus sp.* *Bacillus sp.* *Pasteurella multocida*	Cosmetics, tissue engineering, osteoarthritis, ophthalmology
Chondroitin	*Escherichia coli K4*	Tissue engineering, osteoarthritis
Biotechnological heparosan or heparin	*Escherichia coli K5*	Vascular pathologies: anticoagulants
Marine polysaccharides or exopolysaccharides	*Alteromonas sp.* *Pseudoalteromonas sp.* *Pseudomonas sp.* *Vibrio sp.* *Halomonas sp.*	Cosmetics, tissue engineering, oncology, antivirals, antibacterials...

Fig. 2 – **Bacterial marine polysaccharides as a source of innovative glycosaminoglycan (GAG) mimetics.** ■

Marine micro-plants

In the last 20 years or so, several collections of marine bacteria, micro-algae and fungi, have been established in Europe and worldwide for R&D on optimizing the production of biomolecules, in particular of enzymes and polysaccharides. Thanks to new molecular biology tools and bioinformatics, the manipulation (cloning) and modification (site-directed mutagenesis) of genetic material are possible, with the aim of creating or modifying enzyme activities to optimize the biosynthesis or the activity of the molecule of interest. Thus, the discovery of new especially bioactive compounds from these 'micro-marine plants' is expanding.

The discovery of innovative molecules

Advances in science will enable the emergence of high-added-value biotechnology molecules for many industrial sectors including food, cosmetics, veterinary and human pharmaceuticals. Enzymes, pigments, lipids, polysaccharides and biodegradable plastics molecules are among the most promising molecules. Some molecules are already on the market or under development including anti-tumor molecules, such as cytarabine, aplidine and roscovitine extracted from marine organisms, neurotoxins extracted from micro-algae (phycotoxins), and polysaccharides produced by marine bacteria or micro-algae for cosmetics. Because of their great diversity and structural complexity, marine polysaccharides have multiple biological properties and are hence a source of new therapeutic molecules (Fig. 2). The production of polysaccharides, traditionally extracted from the animal such as chitin and hyaluronic acid or plant macro-resources such as alginates, by marine micro-organisms will accelerate their development for the pharmaceutical industry, where promising applications are expected.

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13. Seafood and public health

Soizick F. Le Guyader and Chantal Cahu

Seafood is an essential component of global food security, with an average per capita consumption of 20 kg per year. Beyond the proposed biomass, it accounts for nearly 7% of the protein intake in the human diet worldwide, but up to 50% for some coastal populations. Seafood is, in some cases, the sole source of several nutrients. However, seafood can also cause poisoning, which must be prevented.

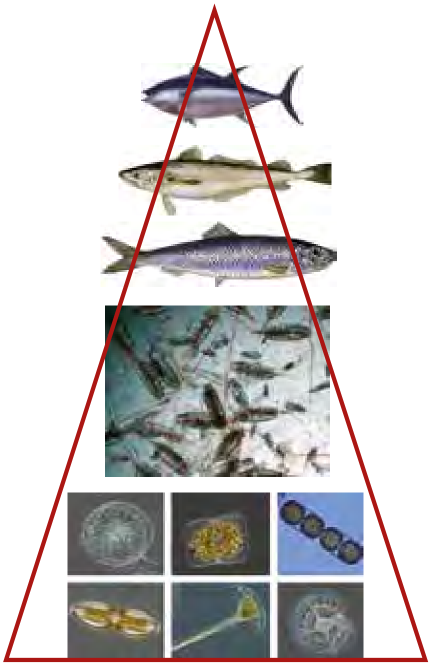

Fig. 1 – **Marine food pyramid, concentrating nutrients and contaminants.** Microalgae, primary producers of organic matter, are ingested by zooplankton. Small pelagic fish feed on zooplankton, and are themselves eaten by the biggest fishes, up to the big predators. ■

The benefits

There are many benefits to be had from consuming seafood, whether caught or produced by aquaculture. Seafood is a source of high quality proteins, its amino acid composition gives it a high biological value. Its nutritional value derives above all from its lipid content, which can vary greatly depending on the species: very low in crustaceans and more than 10 g per 100 g of meat in salmon or herring. The lipids of marine organisms are characterized by their richness in polyunsaturated fatty acids, known as omega 3, these are synthesized by unicellular algae and concentrated along the food chain, and reach very high levels in large predators (Fig. 1).

Many studies have demonstrated the role of these fatty acids in physiological processes. They are involved in the development of the brain and of the nervous system in the fetus and the child, through their incorporation into the cell membranes. They have a proven role in the prevention of myocardial infarction and provide protection against certain cancers, diabetes and neurodegenerative diseases. In addition, seafood is a particularly rich source of micronutrients: pigments with antioxidant potential; vitamins, such as vitamin A involved in vision, or vitamin E fighting against free radicals; and minerals, such as phosphorus, iron, selenium, iodine. All these nutrients have a particularly beneficial action during certain stages of life, including in the perinatal period.

Lipid, vitamin or mineral contents vary in fish flesh, depending on the season, the breeding cycle and the origin (catch or aquaculture) of the fish. The composition of fish flesh depends largely on their diet, and this factor can be controlled in fish farming.

The risks

However, like any food, the consumption of seafood involves certain risks, sometimes directly associated with profits. Indeed, the marine food chain concentrates not only fatty acids, but also all kinds of contaminants, generally lipophilic. Several heavy metals from natural sources or anthropogenic activities are found in the flesh of fish, molluscs and crustaceans. In the case of lead, arsenic or copper, the National Agency for Food Safety (ANSES) considers that the levels generally measured are not a risk to human health. But cadmium levels may be a risk for big consumers. The case of mercury is different. Methylmercury (MeHg), the most toxic form, is easily absorbed and little excreted by living organisms and fish consumption is the main source of exposure. The target organ of MeHg is the brain, both in adults and fetuses, and the effects of mercury exposure were unfortunately well observed in Japan, where an industrial plant located in the bay of Minamata discharged mercury for many years. The ANSES therefore published specific recommendations for infants, pregnant and lactating women (less than 150 g/week of wild predator fish). On the other hand, ANSES considers that the risks associated with organic contaminants and pesticides are very low for the French population.

Toxins, synthesized by microalgae, are also found in fish and molluscs (cf. VI.10). Ciguatera (food poisoning caused by contaminated fish flesh) is a major public health problem for populations of certain tropical islands where large quantities of fish are consumed. Paralytic and amnesitic toxins synthesized by dinoflagellates or diatoms are found in shellfish, which also present risks linked to bacteria and viruses. Their production in coastal areas, where population growth is increasing, favors the risk of contamination by micro-organisms, and their involvement in epidemics has been known for over a century despite the sanitary classification of the production areas (Fig. 2). The bacteria and viruses discharged into the sea by water and by domestic discharges, industrial or agricultural activities can be accumulated by these shellfish. Currently, shellfish-related infections are mainly viral gastroenteritis due to noroviruses. Smaller than bacteria, but much more resistant and rejected in very large quantities, they have long been ignored due to the lack of effective detection devices. Victims of the quality degradation of coastal waters, shellfish are therefore a food that requires strict monitoring. Climatic disturbances, which favor heavy rainfall events, may increase the transfer of pathogens from the terrestrial environment, and the increase in temperature may modify the balance of the marine flora.

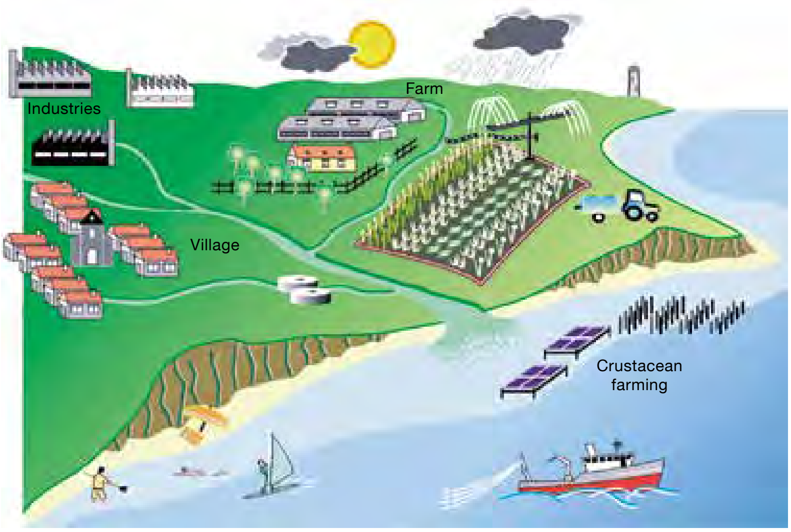

Fig. 2 – **Main sources of contamination of shellfish raised in coastal areas.** Pathogens are the result of various human activities (agriculture, livestock, manure spreading, wastewater discharge), or of leisure activities and are transported in water from the catchment to the sea. Source: LE GUYADER and ATMAR, 2008. ■

Recommendations

Considering the benefits and risks, ANSES recommends the consumption of two portions of fish per week, one of which is rich in fatty acids, varying species and places of supply. This consumption allows optimal coverage of nutrient requirements, while limiting the risk of overexposure to chemical contaminants.

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14. Maritime transport and seaports

César Ducruet and Mattia Bunel

What would economic globalization be without maritime transport and seaports? At present, more than 90% of the volume of world trade is transported by sea, which corresponds to about 70% in value. In 1776, Adam Smith emphasized the impossibility of a land journey between London and Calcutta and the mutual benefits of the maritime route. The 'maritimization of the world economy', dear to André Vigarié, is reflected in a number of recent studies on the positive effects of a coastal option, port efficiency and the reduction in commercial costs for the states involved. However, the current discourse on global connectivity favors daily land, air and telecommunications mobility. Many 'world cities' have abandoned their seaport, which became distant, mechanized, polluting, no longer lucrative and took up too much space. However, maritime transport continues to accompany and facilitate recent economic changes through its vital role in networking the world.

colonial-center-periphery logic that prevailed until the late 1960s, was based on direct and long-distance routes between origins and destinations. The rise of road transport and globalization have since facilitated the implementation of a transit and redistribution logic by streamlining ports of call around major hubs in shorter and massive segments, due to reinforced economy of scales. In this increasingly competitive environment, the major maritime cities of the past have been struggling against the reorientation towards road transport and the uninterrupted technological development of the maritime sector, moving towards ever more concentration and specialization. The liberalization of the sector in the 1990s, like air transport in the 1980s, reinforced this trend (increasing the size of vessels, with new major ship owners' alliances), and even continued as a result of the shock caused by the crisis (2008-2009). The crisis motivated more massification, horizontal concentration and technical adjustments (such as slow steaming), leading to a very selective mega-ships world of up to 400 000 tons deadweight and docking in mega-ports, be they Asia-Europe and Asia-USA Brazil-China containers or bulk, for example. Nevertheless, in a certain way these changes and disturbances remain anchored on structures largely inherited from the past.

By virtue of the long-standing spatio-temporal coevolution between cities and commercial ports, the banishment to the periphery of modern port terminals has only challenged these historical links to the margins of the system, such as mere transhipment hubs for containers or bulk terminals developed on the basis of nearby extraction of natural resources. Rotterdam, Dubai, Singapore and New York remain major maritime

Permanence and changes in the global maritime network

One of the most striking facts of the contemporary period is the increasing centralization of the network around major hubs, which has accelerated since the 1950s. Containerization, often seen as a technological revolution, is said to have reinforced this trend. The

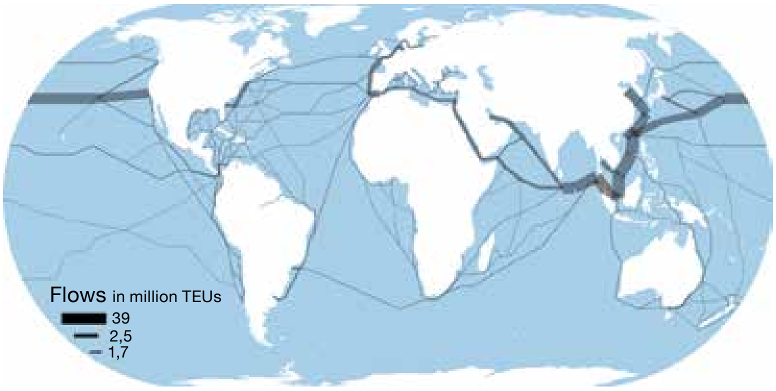

Fig. 1 – **Main containerized routes in 2015.** TEU: Twenty foot equivalent unit. Based on Lloyd's List Intelligence. ■

metropolises, just like London, after a port retreat phase in favor of the City, which recently re-integrated in its heart modern terminals like the London Gateway operated by Dubai Ports World, the same phenomenon being underway in Taipei, Jakarta... Thus, on the basis of an extended definition of the reference point (coastal or inland city and its own and/or satellite terminals), the largest cities in the world maintain their strong lead over others in several respects: global connectivity, volume, traffic value, and diversity. These multifunctional points are said to concentrate more than 80% of the world's maritime traffic today.

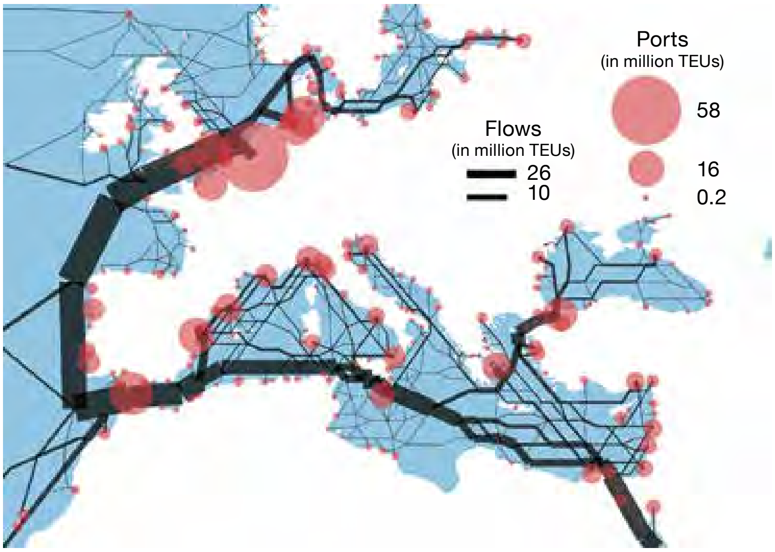

Fig. 2 – **Ports ranked in order of importance and main marine corridors in 2015.** TEU: Twenty foot equivalent unit. Based on Lloyd's List Intelligence. ■

Monitoring global and European maritime flows

Very few printed maps accurately represent the distribution over the globe of these maritime flows for well over a hundred years. While the Internet and increased accessibility to radar and satellite data have recently produced many visualizations, they remain static and are not sufficiently analytical. However, the Geoseastems tool provides a map of global flows in 2015 from four full months of container vessel navigation. The importance of the east-west circumterrestrial route serving the famous Triade - the United States, EEC and Japan - far exceeds that of the transatlantic and north-south links (Fig. 1), although some secondary routes have emerged, Australia/South-East Asia, or South Africa's bypass aimed at avoiding Somali piracy, as well as the cost of going through the Suez canal, but also motivated by the increasing profitability of intra-BRICS trade (Brazil, Russia, India, China and South). The Panama Canal, which was expanded and re-launched in June 2016, could alter this overall pattern by allowing a large proportion of the flows to the west coast of North America to be directly diverted to seaports on the east coast, such as Savannah, which have already invested in large expansion projects in anticipation of these changes.

A zoom on Europe (Fig. 2) clearly shows the Mediterranean corridor, a segment of the aforementioned route that timidly branches off to the north and south of its shores, as well as toward the Black Sea from a string of large hubs. This maritime 'umbilical cord' of Europe ends in the Benelux, Antwerp and Rotterdam being the main continental gateways, bypassing the Iberian Peninsula, France and the British Isles, thanks to a multimodal, logistic apparatus and industrial competition. Antwerp handles about 60% of French foreign trade; Rotterdam and Hamburg polarize North-West and North-East Europe respectively. This quasi-monopoly appears to be well established, despite the efforts of neighboring countries and the European Commission insistence on territorial equity.

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15. Urbanization and the ocean

Iwan Le Berre and Samuel Robert

The sea and the oceans have long fascinated mankind, and for several decades, this has been leading to the concentration of human populations on the shores. In many countries around the world, coastlines are now subject to urbanization and urban dynamics. In the context of climate change, cities located by the ocean raise a number of questions. How can they be protected against the onslaught of the sea? Should their expansion be slowed down? Can they be designed in harmony with the ocean?

Coastal urbanization, a marker of the ocean's attraction

Human societies have historically been attracted to the coast. However, urban settlements long remained occasional one-off events around port sites, to exploit resources from the sea, organize trade flows and ensure control of maritime areas (Fig. 1). Since World War II, massive urbanization of the coasts has been the result of economic development, the maritimization of trade, and subsequently of the growth of tourism and the leisure industry. Nowadays, alongside industry- and port-based urbanization, residential and tourism-based urbanization (hotel complexes, seaside resorts, marinas, condominiums) dominates the landscape, often in a very wide variety of forms (Fig. 2). In some developing countries, this is intensified by often poorly controlled urbanization, giving rise to informal urban extensions (slums or spontaneous residential developments) housing people in search of employment and a better future.

Assessing human population density on the shores of seas and oceans is not easy. Based on various methods, assessments produce figures that are not always convincing, since the geographical delimitation of coastal areas can vary. According to the most recent estimates (Institute of Geography, Kiel, 2015), based on figures for the year 2000, nearly 11% of the world's population (625 million inhabitants) live in coastal areas at an altitude below 10 m. The population is highly concentrated, reaching densities of around 241 inhabitants/km^2, more than five times higher than the world average. Projections show a tendency towards increased density, with the coastal population potentially reaching 900 million inhabitants in 2030, and 1.4 billion in 2060, corresponding to 534 inhabitants/km^2, more than double today's figure.

Urbanization and disruption of coastal dynamics

But the attractiveness of the sea and the coast also creates problematic situations. Cities, areas of economic activity and trans-

Fig. 1 – **Brest and its harbor.** Maritime cities base their existence and development on their port, whether military, commercial, fishing or pleasure (or all at once). © L. NÉVO / Brest métropole. ■

port infrastructure are extended to the detriment of natural and agricultural areas, which often disappear at a worrying rate. For example, several cities have been built on former, rehabilitated marshlands (Boston, Amsterdam, Venice, Tokyo) and many seaside resorts have been built on dunes or lagoons. The regression of these therefore rare coastal environments has significant repercussions on marine ecosystems. Locally, traditional economic systems based on coastal resources are threatened, as coastal geomorphological dynamics are disrupted.

Today, many cities built on soft substrates on the coast or on dunes are exposed to serious problems of erosion. Seaside resorts are seeing their beaches disappear (Côte d'Azur, Balearic Islands, Australian Gold Coast) and are striving to restore them at a high price. Elsewhere, under the weight of urban construction, the natural subsidence of many deltas, and of the cities established there (Bangkok, Venice, New Orleans), is accentuated by the overconsumption of water and the scarcity of sedimentary deposits. To an ever increasing extent, by spreading and developing, cities are disrupting natural dynamics and are faced with an ocean whose level is rising and whose assaults will multiply.

Fig. 2 – **Residential urbanization affecting the shore and hills, Bodrum Peninsula (Turkey).** © S. ROBERT. ■

Tomorrow's coastal urbanization?

At global level, the growing trend towards urbanization of coastal areas – exemplified by Dubai and Monaco – and the impossibility, or at least the great difficulty (technical, economic and social), of dismantling cities on the coasts make urbanization likely to remain a long-term coastal feature and issue. This suggests the need to consider how best to maintain existing settlements and to design any future ones. Urbanization no longer simply faces the ocean: it has to deal with the ocean.

Already, innovations in city design are in progress and examples for tomorrow are being developed. For example, in Jakarta, to combat the risk of marine submersion, protective structures incorporating new urban spaces are projected in such a way that limits their environmental impact. In order to reduce their carbon footprint, Copenhagen, Honolulu and Marseille are taking advantage of the sea as an energy reservoir by constructing sea-water loops that supply certain districts with heat and air conditioning networks. Floating cities are being designed and old submarine habitat projects are resurfacing. These initiatives reflect the great capacity of human societies to innovate to overcome adversity and adapt to new environmental challenges. But they also raise questions about the sustainability of such developments, especially since plans for the coastal city of tomorrow cannot simply be based on engineering. More than ever, scientific communities need to work together with citizens to design it. A challenge that is both immense and stimulating for research.

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16. Desalinating seawater: a sustainable solution?

Agathe Euzen and Corinne Cabassud

In the context of global change, from global warming to rapid urbanization, the shortage of fresh water is becoming a major problem in the 21st century. More and more countries are experiencing water stress (a situation caused by a shortage of water of satisfactory quality, with insufficient quantities to meet the needs of humans and the environment). Meanwhile, there is ever-growing demand from domestic uses and agriculture. However, fresh water resources are becoming scarcer, their quality is falling, and they can no longer satisfy all needs, including the basic needs of certain countries or isolated zones. The world's population is becoming concentrated on the coasts, where the megacities of tomorrow are being built. In the future, could desalinating seawater provide an alternative solution to fresh water shortages in certain regions of the world?

Desalination plants

In 2013, there were 18,400 operational desalination plants in the world (IDA, 2013). Desalination allows us to produce 80 million m^3 of fresh water per day, and is growing by around 10% per year. Desalination plants are setting up in all regions of the world, but 10 countries account for 40% of production, with Saudi Arabia in the lead (9.2 million m^3 per day), followed by the United Arab Emirates (8.4 million m^3 per day). These countries are in desert zones, and have large energy resources. Spain ranks third with 3.8 million m^3 per day.

A desalination plant can carry out several operations. The choice depends on the local context, the proximity to the saline resource (sea, ocean, brackish water), its quality (including its salinity), the target production capacity and the kind of energy available. Today, two processes are used. The first is reverse (membrane) osmosis, where sea water is forced through dense membranes which let the water molecules through, but trap the dissolved salts. This process uses a high-pressure pump (around 65 bars), because its pressure must be greater than the osmotic pressure caused by the water's salinity (*i.e.*, greater than the force pushing the water to move from the more concentrated to the less concentrated solution until an equilibrium is reached). The recent development of pressure recuperators and of effective membranes has helped reduce energy requirements, and reverse osmosis is now the most widely used desalination technique in the world. Another technique,

Seawater desalination plant in Doha, Qatar (2015). Source: tpe103eau.wordpress.com. ■

(thermal) distillation, involves boiling the water. In this case, the salt is not vaporized, and the desalinated water is recovered through condensation on a cold surface. Several studies show that combining distillation and a membrane procedure (membrane distillation) can make desalination more effective, by increasing productivity and reducing discard volume.

To make the processes effective, pre-treatment operations (chlorination, coagulation, pre-filtration, and scale prevention) are required. For example, a massive development of algae can adversely affect desalination operations. Therefore, pretreatment must in particular allow the retention of algae, whilst avoiding discharge of toxic microcystins (toxins from the most common blue algae in the water). Similarly, the freshwater produced generally goes through specific treatment, adapted to its final use. Most often, it is rebalanced and mineralized, to meet drinking water standards in the country in question. For irrigation, the presence of boron in seawater means that a specific operation is required to reduce the concentration of this substance, because it is toxic for plants.

How can desalination be sustainable?

Several variables influence the cost of desalinating seawater and the cost price per metre squared of fresh water obtained. These are: the process and its energy requirements, but also, upstream of this, the quality of the harvested seawater, its salinity level and the plant's production capacity, and downstream, the infrastructures and networks needed to distribute the water. To reduce the energy cost and the price per metre cubed, and to supply isolated zones, recent facilities use renewable energies (wind, solar, photovoltaic) or recover lost energy (*e.g.* from warm water).

Moreover, often located in shallow, coastal seas, the pumping zone can degrade marine ecosystems such as seagrasses, which are a feeding habitat for fish. Desalination units produce chemical and brine waste, which requires specific treatment and careful selection of discharge sites, to protect the environment.

How can the resource be used?

On a large scale, the water desalination solution often accompanies the growth of coastal megacities, particularly in the Mediterranean. In these cities, which are popular with tourists and heavily frequented in the summer, using desalinated water could provide an alternative way of meeting heightened seasonal demand, as in Barcelona. However, this poses the question of the additional costs of building new infrastructures, sometimes a double network (which needs maintenance and management), and of knowing who will be connected, since some residents would prefer to drink other water, even if it is less accessible or of a lower quality.

In certain isolated coastal villages with limited access to fresh water and without fossil energy, or in emergencies (floods, earthquakes), small, energy-autonomous units can be used to treat seawater. They need to be robust and adapted to local social, climatic, environmental and regulatory conditions. Their set-up must be accompanied by training for operating and maintenance staff, to allow rapid intervention and transfer of skills.

At the same time, in certain countries such as southern Spain, desalinated water has been offered for use in irrigating crops. However it cannot meet the needs of all the farmers concerned, because the price per metre cubed is too high and the quality is not adapted to their requirements. So should we keep using energy and investing in desalination units, to provide water for irrigation or leisure activities in regions that already have too little fresh water to meet their basic needs? Instead, should we not prioritize improving the adaptation of agricultural and tourism activities to the local climate context?

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17. The ocean as a sporting challenge: offshore races

Nicolas Bernard

Until recently, the sea was the scene of mainly economic or geostrategic activities conducted by nations with a maritime tradition. This involved the exploitation of ocean resources (biological or mineral), the transport of goods or passengers, the presence of military fleets... In the field of tourism, 'edutainment', cruise ships, boating and maritime sports activities all became popular during the second half of the 20th century. Although a few pioneers of ocean sailing showed the way, the use of the ocean for sporting purposes did not become popular with the general public until the end of the 1970s, when offshore nautical competitions multiplied and found a hitherto unknown echo in the media.

The importance given to these regularly organized nautical events leads us to question how they change our perception of maritime and oceanic spaces. How can these sporting events take on such significance in our societies when many spectators have little or no knowledge of this ocean environment

Challenging the ocean expanses

Offshore racing can be defined as a nautical competition that takes place far away from the coast with only the sea as a horizon. Beyond this functional definition, this activity has a symbolic dimension composed of myths and powerful images as well as of human and aesthetic values. Its popularity is partly explained by this dimension. Offshore racing is a sports activity that covers a wide range of nautical competitions involving a single skipper or a skipper and crew, with or without stops. These can be round-the-world races (Fig. 1), transoceanic races and offshore races (like 'Solitaire du Figaro'). The notion of a race is indispensable to ensure the sporting and media interest of a particular event. Speed introduces a new relationship between human beings and an ocean environment. Records continue to be broken one after the other, suggesting that the ocean has become an environment with a human dimension (Fig. 2).

Offshore racing resembles any other sports competition because,

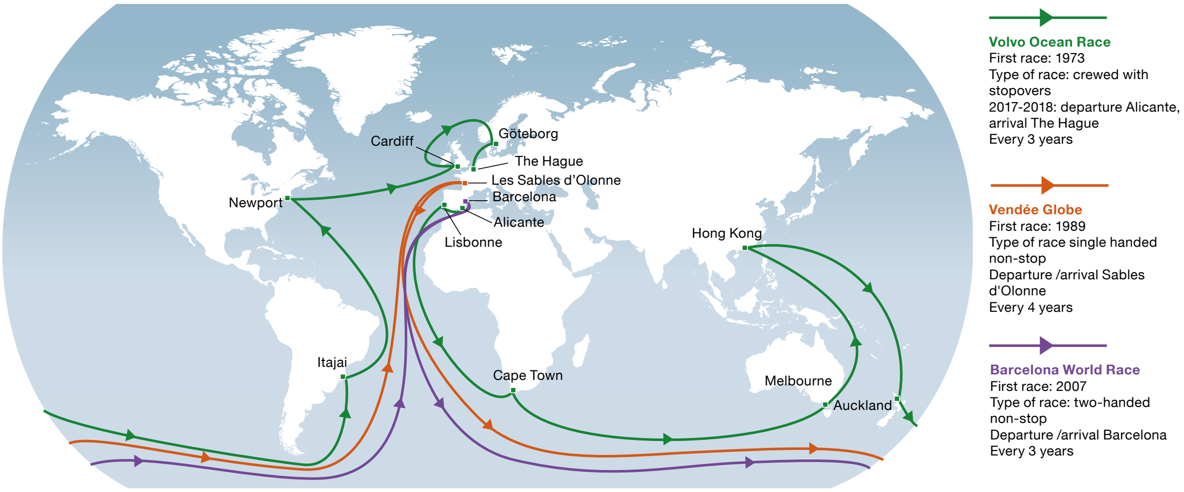

Fig. 1 – **Three main round the world yacht races.** © LETG / UMR6554 / CNRS. ■

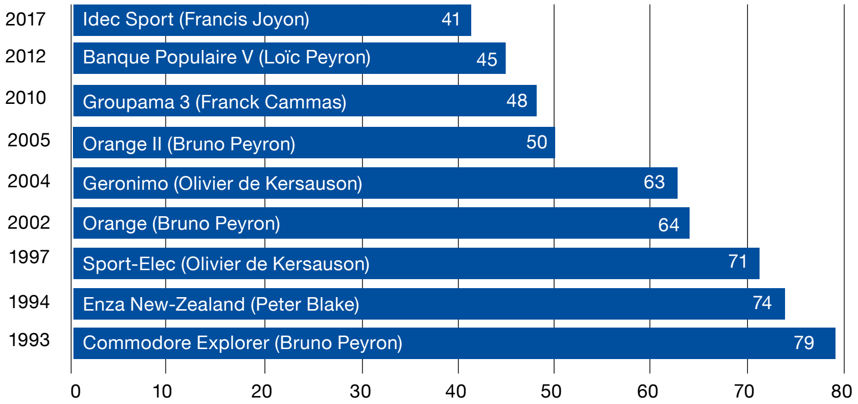

Fig. 2 – **Jules Verne Trophy (crew race round the world departure from Brest).** Records (number of days). ■

aside from the fact that the navigator is also pitted against his/her competitors or has a record to break, he/she must also confront the 'natural elements': the sea, wind and currents. The skipper has to deal with these and use them to gain speed. Offshore racing, like other extreme sports, embodies the 'transcendence of self' and is a contemporary expression of courage. It also carries within it the dream of distant horizons and human adventures in this ocean universe which is considered by many to be the 'last space of freedom' on the planet.

Racing allows the spectator, although not personally involved, to experience this adventure vicariously. The skipper is generally considered as an exceptional character and, for this reason, is more an object of admiration than of imitation. If the offshore race materializes the idea of men and women challenging the natural elements, other notions arise which paradoxically break away from a naturalistic dialectic and draw attention to motorsports: speed, setting parameters, risk- taking, navigating... It is this combination of the two fields, that of nature and that of high technology, that the skipper embodies. The symbolic force of offshore racing stems from this combination of sporting, technological and human challenges.

The ocean, a nautical stadium

Maritime spaces do not require any special arrangement for the organization of the sports events. They simply occur at irregular intervals by fleets of boats designed for such competitions. However, the name 'nautical stadium' deserves to be retained; it cannot be defined solely on the basis of planning and equipment criteria. Indeed, thanks to localization, communication and retransmission devices, it is only a space that serves as a framework for sports practices that can be followed continuously by a large number of people. Thus, for thousands of enthusiasts, offshore racing is no longer limited to a simple departure and arrival point: they can now watch the entire show, thanks to the images transmitted live by the skippers themselves in which spectators actually see them maneuvering their sailing craft. The time when Eric Tabarly surprised everybody (including himself!) by emerging from the mist-enshrouded harbor of Newport (Rhode Island) to win the victory in the English Transat of 1964 now belongs to the history of offshore racing.

Today, thanks to technological progress, it is possible to know in real time the position of the competitors and their ranking, as if it were a stage of the Tour de France. If the 'nautical stadium' is not physically filled with spectators, it is filled, virtually, with spectators who follow the race from their computers or their smartphones, or simply *via* the media. The success of online games offering offshore racing simulations (Virtual Regatta, for example), also reflects this passion.

Despite their length, transatlantic races resemble other major sports competitions, with pre-race fever, reports on the spot, intense media coverage, the weight of the socio-economic stakes and the involvement of sponsors. But even this standardization cannot undermine the difficulty and prestige of such tournaments, which, after all, represent a challenge at oceanic scale.

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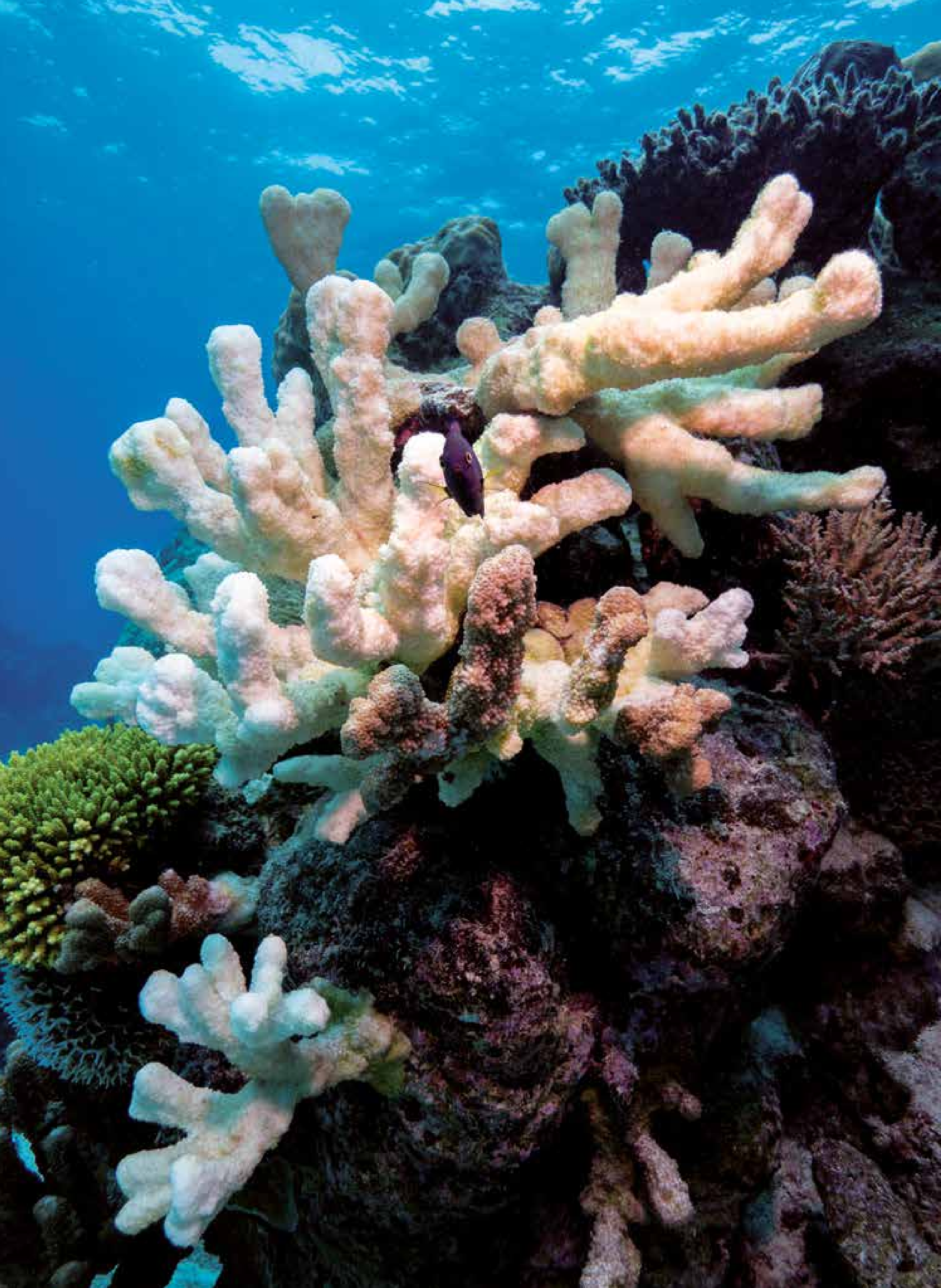

- PART SIX -

The risks

Previous page:

Coral bleaching in New Caledonia. © IRD / J.-M. BORÉ. ■

1. Introduction

François Galgani, Nadine Le Bris and Jean-Pierre Gattuso

According to the most recent global assessment of the marine environment published by the UN in 2015, human activity is having a significant effect on 40% of the world's oceans, with impacts that include pollution, the depletion of fishery resources and the disappearance of coastal habitats, whilst major shifts induced by global change are already being seen. The UN's sustainable development goal 14 for the oceans underlines the interdependence between biodiversity, its associated ecosystem services and the impacts of these changes on marine ecosystems. More recently, declarations by the G7 and G20 have provided some guidance on current problems with pollution, and they supplement global and regional initiatives under the United Nations Environment Programme (UNEP) which are in turn transposed into European directives. In France, the law on the restoration of biodiversity, nature and landscapes, enacted in 2016, aims to protect, restore and enhance biodiversity and in particular, to prevent, reduce and offset the negative environmental impacts of certain human activities. This law is directly relevant to the oceans and related major changes, and we need to develop the knowledge and analysis tools – vital management resources – to understand these. The concept of risk assessment appears crucial in this context. We have to understand how far ecosystems can be disrupted before they reach a threshold beyond which changes are likely to be irreversible. Expanding research to address gaps in knowledge, in a field where observation is still piecemeal, is a major challenge which needs to drive support for measures designed to mitigate these risks.

In addition to natural events, the risks of irreversible human impact on the marine environment are real. © F. GALGANI / Ifremer. ■

The oceans face a host of influences which may affect how they function. These may be natural, like geological, seismic and gravitational hazards, but they also derive from human activities. Currently, around 40% of the world's population lives less than 100 km from the coast, and the more these numbers increase, the more the discharges into the sea weaken these ecosystems. There are also large-scale impacts linked to the increase of CO_2 in the atmosphere, with multiple global effects – warming, acidification and deoxygenation of seawater – and consequences.

While it is no longer disputed that the dysfunctions of the oceans are of human origin, uncertainty still persists regarding the extent of these problems and the rate at which they occur. Their direct expression and their interaction with each other have an impact on the taxonomy of the biosphere. Overfishing, loss of biodiversity, chemical, biological noise or plastic pollution, development along the coastline, dystrophication and eutrophication all pose risks for increasingly fragile ecosystems. This chapter describes the mechanisms that affect the oceans, along with their impacts on the environment and in particular, on the taxonomic groupings for which the effects could be irreversible, as in the deep sea environment or on small islands. For other environments, mitigating the consequences of adverse human activities such as resource deterioration, health risks, the fragmentation of the coastline and species displacement requires urgent intervention, to prevent the most significant risks or find appropriate solutions. This is still possible, if the measures adopted are appropriate to the challenge.

2. The sea, a territory of earthquakes

Louis Géli

The sea, a territory of earthquakes

Most earthquakes are caused by the movement and friction of lithospheric plates around the surface of the globe. Although some earthquakes occur inside plates far from their margins and can be very violent, more than 95% of the seismic energy on the Earth's surface is released at the borders of the plates, mainly located in the ocean (subduction zones, dorsal zones, fracture zones). Thus, submarine seismic activity is the most widespread on the surface of the globe (cf. II.19).

The areas where populations are most at risk are the Africa-Eurasia-India convergence area, encompassing the Mediterranean, the Iran-Pakistan-Afghanistan region, Central Asia, Northern India and China; the circum-Pacific subduction domain, encompassing North-West America, Central America, South America and East Asia (Japan, Taiwan, Philippines, Indonesia, Papua); and volcanic arcs, such as the Antilles and the Caribbean (Fig. 1). In coastal areas, the risks have increased since the acceleration of urban concentration in the 20th century. For example, the earthquake in Guadeloupe, which killed 3,000 people in 1843, would now probably cause more than 100,000 deaths throughout the entire West Indies. This, and the risks associated with submarine environments (gravity collapse, shoreline changes, and tsunamis), make research in this area a major challenge.

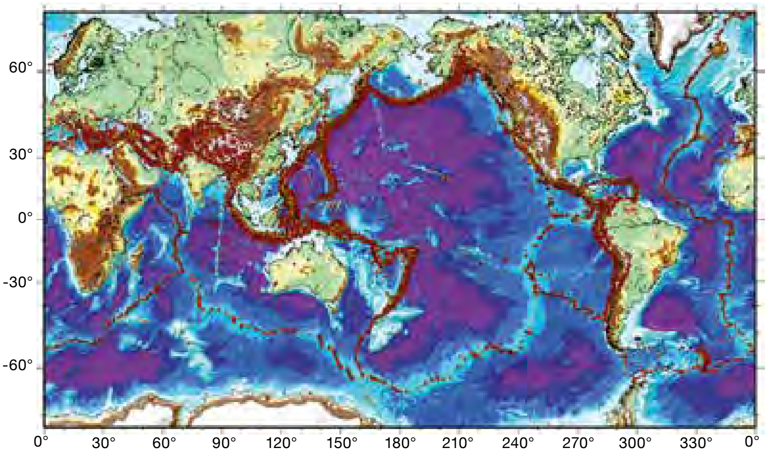

Fig. 1 – **Map of global seismicity (red dots) from 1973 to 2004.** Source: USGS. ■

Induced hazards

Knowledge of the tsunami hazard has increased significantly in recent years, following the disasters in Sumatra (2004) and Fukushima (2011). But much remains to be discovered, especially in the eastern Mediterranean, where the great 365 AD Tsunami ravaged the port of Alexandria and flooded the Nile Delta. Tsunamis are mainly caused by earthquakes or landslides, or explosions of volcanic islands. The devastating tsunami of December 26, 2004, which killed more than 280,000 people, reminded the general public what such a phenomenon could be in the most extreme case, associated with a subduction earthquake of magnitude greater than 9. This phenomenon has however already occurred and may still occur on the coasts of Europe. The tsunamis of Lisbon in 1755 and Messina

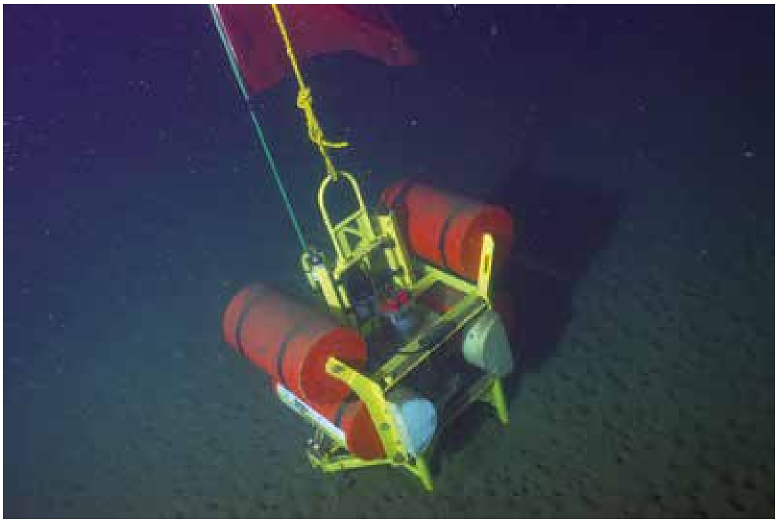

Fig. 2 – **Seismic monitoring involves the deployment of seismographs on the seabed, as shown here, one thousand meters deep in the Sea of Marmara, in the region of Istanbul.** © Ifremer. ■

(which caused more than 100,000 deaths) in 1908, are among the five most devastating tsunamis in history. Today, two approaches are preferred to limit the effects of tsunamis in exposed coastal areas: warning systems to trigger the evacuation of populations before the arrival of a tsunami and taking the tsunami risk into account in the design of structures.

Gravity phenomena in the ocean linked with the seismic hazard have only been studied since the second half of the 20th century. A seismic shock causes a sudden increase in gravity, capable of mobilizing unstable deposits present at the top of the slope. The resulting land movements are responsible for mass transfers of coastal sediments to the deep sea. These movements shape continental margins and ocean basins by repeated accumulation of transported sediment. In the ocean, this mode of transport, called 'turbiditic', is extremely efficient, due to the presence of water. Seismic stress affects the equilibrium of the fluid contained in the sediment pores and increases interstitial pressure, which has the effect of reducing the shear strength of the sedimentary cover. This overpressure may be sufficient to destroy the soil's cohesion (the liquefaction phenomenon), to trigger a slide in extremely vast zones (of several tens of thousands of square kilometers), with a very low slope (much lower than in the continental domain).

Ocean-specific approaches

Underwater seismicity differs in several respects from terrestrial seismicity in particular due to the presence of fluids in active structures, but also due to problems of observation. The deep ocean remains a hostile environment and marine research requires significant resources. Hazard assessment involves integrated actions with oceanographic vessels and heavy tools that are difficult to use and costly to maintain: seismographs (Fig. 2), sea bottom observatories...

Sea bottom observatories

To pursue our research, we need to address the triggers and physical properties of submarine faults using specific and innovative approaches. This involves deep sea drilling programs and the establishment of permanent observatory networks on the seabed.

In the ocean, active faults are usually associated with fluid outlets. Understanding the relationships between fluids and seismicity is therefore a crucial issue. In Japan, investments of several hundred million euros have been made to try to detect fluid movements associated with large subduction earthquakes, notably with the construction of the Chikyu drilling ship. Simultaneously, other major programs are being set up for permanent multidisciplinary observatories on the ocean floor: DONET in Japan, Neptune in Canada and the United States, and EMSO in Europe.

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3. Risks related to climate change

Jean-Pierre Gattuso and Alexandre K. Magnan

The ocean functions as a 'climate integrator' and limits the impact of climate change in two main ways. On the one hand, it absorbs almost all the heat that accumulates: over the last 50 years, it has stored 93% of the excess heat produced by the increase in the greenhouse effect at its own expense, *i.e.* storage resulted in ocean warming and a rise in sea level caused by thermal expansion and melting polar ice caps and glaciers. On the other hand, since 1750, the ocean has absorbed 28% of carbon dioxide (CO_2) emissions resulting from human activities, thereby increasing seawater acidity (Fig. 1).

Oceans thus implement climate regulation to their own detriment. Although less spectacular than the rise in sea level, the associated physical and chemical disturbances greatly affect marine ecosystems and consequently mankind. For example, ocean acidification and warming complicates the calcification of essential marine organisms (corals, shells); many coral reefs are bleaching as a result of the disruption of the symbiosis they maintain with algae; phytoplankton biomass is decreasing in the warmest regions; the fish food chain is being disrupted; many species are migrating to colder regions, but not all of them can..

Impact on ecosystems

There many consequences for marine ecosystems and the services they provide to human societies. Two scenarios can be considered: CO_2 emissions continue to rise according to the current trend (worst case scenario) or CO_2 emissions are reduced to limit the rise in global temperature to 2 °C over the course of the 21st century (optimistic scenario, compatible with the Paris Agreement).

Depending on the CO_2 emission scenario, the acidity of seawater will have increased by between 38% and 170% between the industrial revolution and the end of the 21st century (cf. II.9), while the average sea level will have risen by between 60 and 86 cm between 1901 and 2100 (cf. II.15). Finally, the oxygen content of the ocean will continue to fall at a rate that also varies with the emission scenario, and will affect underwater life in all its forms.

Tropical corals are already seriously affected by warming and acidification, as are mid-latitude marine plants, pteropods (planktonic molluscs) and high latitude krill, low latitude bivalve molluscs and fish in general (Fig. 2). Under the optimistic scenario, only the

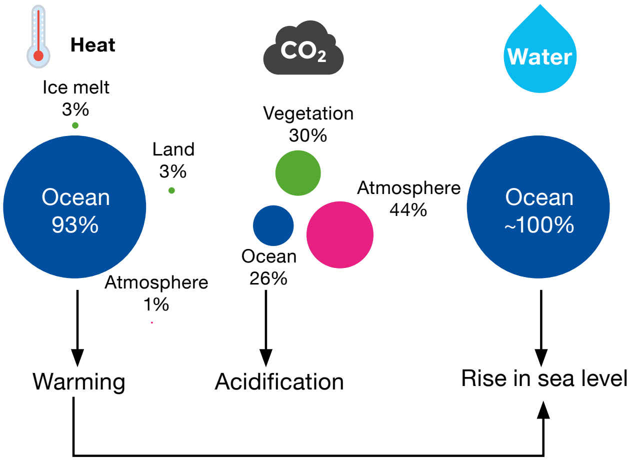

Fig. 1 – **Distribution of heat, carbon dioxide and water resulting from ice melt in the main reservoirs of the planet and impacts on the ocean.** Adapted from GATTUSO and MAGNAN, 2015. ■

status of tropical corals and mid-latitude bivalves will continue to be of major concernwhereas, under the pessimistic scenario, warming will have a disastrous impact on all of these organisms, with large scale migrations, mass mortalit and a decrease in marine biodiversity in the intertropical zone. The results obtained in experiments, in field observations and in model projections, are in agreement with the results of studies of other periods in the history of our planet that were characterized by a notable presence of atmospheric CO_2 , in particular linked to volcanic activity.

The effects on human activities will also follow a negative trajectory that varies depending on the CO_2 emission scenario. If the current pace of emissions continues, fishing will be seriously compromised, especially in the intertropical zone, where it is a vital source of protein and provides an income for millions of people. The impacts would be equally daunting on coastal ecosystems, whether they are used to protect land (coral reefs, mangroves, seagrass beds), or sites of aquaculture or tourism.

Time for solutions

The damage caused by warming, acidification, and sea level rise to marine organisms and ecosystems, and the services they provide is already detectable and is likely to increase in the future, even under the optimistic scenario. They will be accompanied by other pressures caused by human activities, including the overexploitation of living resources, destruction of habitats and different types of pollution. Given the scale of the expected disturbances, it is essential to realize that no country will be exempt and that the traditional North-South split does not apply.

What are the solutions? In addition to mitigating and eventually have zero net CO_2 emissions , the 'international community' will have to ensure the protection of marine and coastal ecosystems, the restoration of those that have already been damaged, and give societies that depend on maritime resources the opportunity to adapt. Some of these measures are already being tested at the local level, but room for maneuver is shrinking as the world moves away from the +2 °C target and the oceans are in the process of heating up and acidifying. For example, more degraded coral reefs will have less ability to resist climate change, and will be more difficult to rescue. Other possible solutions are more controversial, *e.g.* the so-called 'solar radiation management' techniques, which would artificially reduce global warming by increasing the amount of radiation reflected towards space: a solution that might counter incentives to reduce CO_2 emissions and would consequently provide no remedy for ocean acidification.

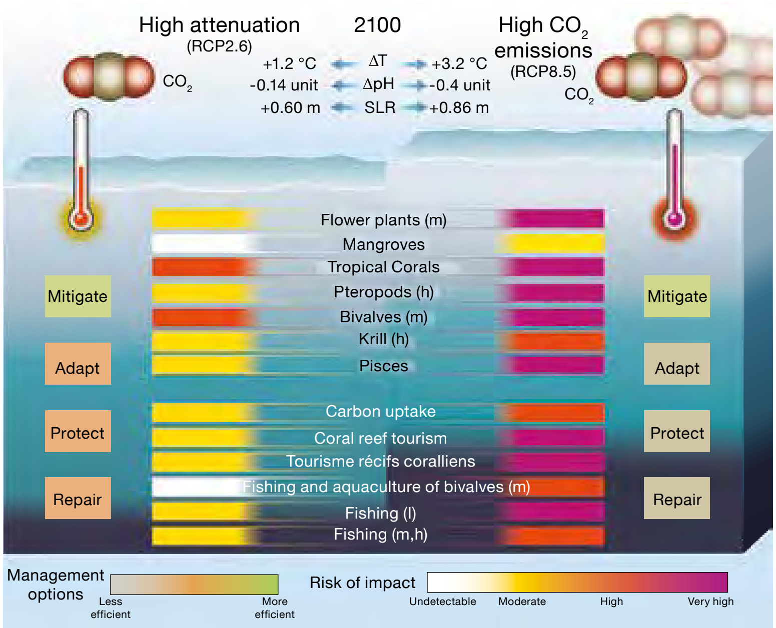

Fig. 2 – Effect of carbon emissions on the ocean. Adapted from GATTUSO *et al.*, 2015. ■

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4. Climate engineering and the ocean

Stéphane Blain

The ocean is a carbon sink: it absorbs carbon dioxide (CO_2) from the atmosphere and stores it (cf. II.14). The duration of the sequestration essentially depends on the depth at which the CO_2 is stored, but also on its physicochemical form. The mechanisms involved in carbon storage in the ocean are called pumps. The solubility pump relies on oceanic circulation, which transports inorganic carbon (CO_2, hydrogencarbonate and carbonate) from the surface to the deep seas. This mechanism currently absorbs around a third of anthropic CO_2 emissions. The biological pumps are based on the transformation of inorganic carbon into particulate carbon, which gravity then transports to the deep layers of the ocean. A very small amount even reaches the ocean floor, where the carbon is stored for geological time scales. The biological pump based on organic carbon is highly dominant in the natural oceanic carbon cycle, but it does not currently contribute to the storage of anthropic CO_2 emissions. Climate engineering techniques in the ocean aim to deliberately make the natural pumps more effective, so that they trap more carbon, thereby reducing the quantity remaining in the atmosphere.

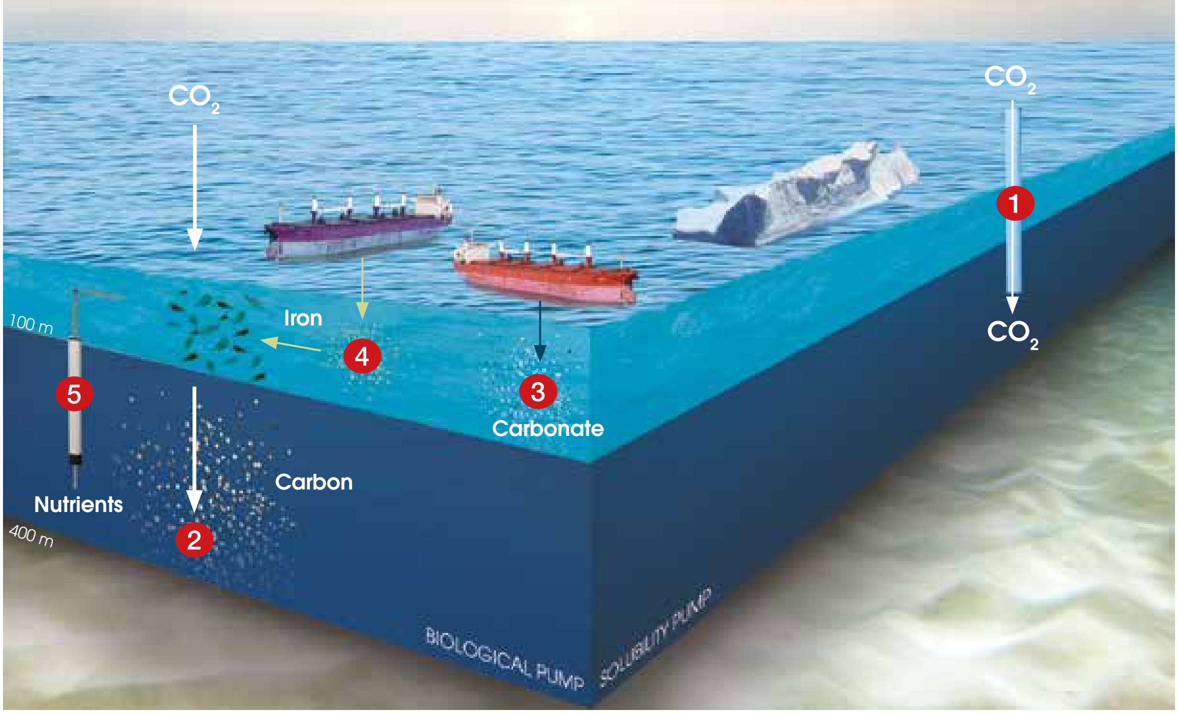

Diagram illustrating the two main natural CO_2 pumps and the main climate engineering proposals based on their manipulation. 1) Solubility CO_2 pump. 2) Biological CO_2 pump. 3) Climate engineering through alcalinization of the oceans. 4) Climate engineering through artificial fertilization with iron. 5) Climate engineering by pumping of subsurface waters (fertilization with nitrogen and phosphorus). © E. GODET. ■

The different techniques

For the solubility pump, the most frequently mentioned climate engineering technique is 'alcalinization of the oceans', which involves artificially increasing the quantity of CO_2 that can be dissolved in the surface waters, by adding lime. We have comprehensive knowledge of the theoretical bases of CO_2 dissolution and large-scale oceanic circulation, so this method is relatively well understood and predictable. Alcalinization of the oceans would also reduce surface acidification. Nevertheless, we can predict major side-effects on land, due to the extraction and treatment of the enormous quantities of carbonate rock required.

For the biological pump, the oldest climate engineering proposal is based on artificial fertilization of large oceanic regions. The biological carbon pump in the Southern Ocean is relatively inefficient. Small-scale artificial fertilization experiments using iron, along with observations of environments that are naturally rich in iron, have shown that adding this element stimulates photosynthesis, and therefore the formation of organic carbon. Moreover, according to certain hypotheses, the Southern Ocean was heavily fertilized during the Ice Age, by inputs of atmospheric dust, thus contributing to the observed reduction of atmospheric CO_2 during such periods. Nevertheless, it has still not been proven that large-scale fertilization of the Southern Ocean would allow us to significantly reduce atmospheric CO_2. The first danger of this technique is the simplicity with which it can be implemented, as illustrated by the fertilization conducted in the North Pacific in 2012, outside of any scientific control, under the alibi of an attempt to restore salmon populations. Moreover, massive and ongoing fertilization of the ocean would undoubtedly provoke numerous side-effects for marine ecosystems. These effects have not yet been seriously evaluated. They could be local, affecting the ecosystem of the fertilized zone, but there could also be 'downstream' impacts on the dynamics of oceanic zones far from the fertilized area.

The other climate engineering approach based on stimulating the biological pump concerns the tropical regions. In these regions, the surface waters have low levels of key nutrients (nitrogen and phosphorus). In contrast, there are large quantities of these elements in the subsurface waters, hence the idea of creating artificial upwelling of deep waters, to stimulate biological production and the trapping of carbon at the surface. The proposed technology uses large tubes, which create a connection between the surface and the subsurface, while the swell of the ocean allows water to move up the tube. However, the experiment conducted off Hawaii was entirely inconclusive, because the pumping technology did not work. Furthermore, there are still many uncertainties regarding the true effectiveness of the procedure for storing carbon. For example, the deep waters are also rich in CO_2, and this artificial upwelling could eventually lead to CO_2 degassing, creating the opposite effect to that desired. Generally, compared with iron fertilization, there has been little research into this procedure, but we could expect a similar set of side-effects, because both approaches manipulate marine ecosystems.

Side-effects

Generally, the assessment of all climate engineering techniques designed to modify both marine and terrestrial carbon sinks must take into account the 'rebound' effect. The increase in the CO_2 absorption of a natural carbon sink first depends on the rate with which the atmospheric CO_2 content is rising. If a climate engineering method can significantly reduce atmospheric CO_2, then the natural carbon sinks (the ocean and continental biosphere) could become sources of carbon for the atmosphere.

The evaluation of engineering techniques with global effects faces the same question as climate or environmental sciences: how do we provide proof? To do this, we need to combine observation, modelling, simulations and experimentation. Nevertheless, for experimentation, there is a fine line between researching on the technique and implementing it. This is not the only difficulty: beyond the scientific and technical aspects, many other issues (ethical, political, economic, legal...) must be considered.

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5. Marine flooding, coastal erosion and shoreline retreat

Gonéri Le Cozannet and Manuel Garcin

Far from being stable, coastal fringes constantly adjust to their maritime and terrestrial environment. The morphology of the coast changes under the influence of winds, waves, currents, and tides. These changes are accompanied by marine flooding and coastal erosion phenomena (Fig.), erosion being responsible for coastline retreat. These physical phenomena become risks only when they threaten human, environmental or economic assets. Today, coastal risks have become a major concern. Indeed, the increasing exposure of people and the coastline issues that have arisen since the 20th century are difficult to accommodate with the constantly evolving shorelines and the occurrence of sometimes very deadly floods (the North Sea storm in 1953 and Xynthia in 2010, tsunamis in Sumatra and Japan in 2004 and 2011, the hurricane Katrina in the Gulf of Mexico in 2005, and Nargis in Burma in 2008). Faced with these threats, exposed societies have implemented prevention and adaptation strategies. Thus, spending on the prevention of erosion and the risk of flooding is reported to be between €3 and €5 billion per year in Europe (Eurosion, 2004). These costs will increase significantly during the the course of the 21st century, due to the rising sea level caused by climate change. Limiting these costs would require the reduction of greenhouse gas emissions and concentrations in the atmosphere, which alone could limit the pace of the rise in sea level to rates that would give coastal societies the time to adapt (cf. II.15).

A physical phenomenon

Marine submersions are temporary floods of usually emerged coastal areas. They may be caused by tsunamis, but usually result from the temporary rise in sea level caused by storms and cyclones. This rise is due to the combined effects of wind, reduced atmospheric pressure and waves breaking near the coast. Depending on the characteristics of the event and the morphology of the coastal areas, a rise in sea level can submerge low lying areas due to overflowing, through waves overtopping the dunes or coastal defenses, or due to the failure of a structure.

Erosion is the result of the loss of materials from the coastline. This include, for example, cliffs collapsing, sand being removed from beaches by waves and currents, or even transported by the wind in dune systems. In undeveloped areas, these erosive processes may cause coastline retreat. On artificial coasts where the coastline is anchored by structures, erosive processes cause morphological modifications of the pre-beach area or of the beach itself, which in some cases can disappear.

Coastline retreat is therefore merely the combined result of many physical processes. In mainland France, about 40% of the sandy beaches were affected by a coastline retreat between 1990 and 2000 (Eurosion, 2004).

Coastal risks

Coastal risks result from the meeting of two factors: first, hazard, defined by the intensity and the return period of the above-mentioned physical phenomena; second, human, environmental or economic vulnerability to the physical phenomena at the very root of such coastal risks. In the case of the marine submergence hazard, the intensity can be defined by the height and velocity of the water flow. The return period is estimated either from the frequency of events observed by tide gauges

Examples of damage to homes resulting from: a) marine submersion and b) erosion of the dune frontline during the Xynthia storm in 2010; c) and d) erosion at Ouvéa and Ronhua (New Caledonia), attributed to the combined effects of decadal or secular changes in sea levels and wave conditions. Source: Observatoire du Littoral, New Caledonia. ■

(often only from the middle of the 20th century on) or from historical archives. In the case of coastline retreat, the hazard is described by a characteristic duration at the end of which the sea will have overflowed a given territory. The risk assessment will differ depending on the type of vulnerability and the intensity of the hazard. Thus, for human stakes, vulnerability to marine submersion caused by a storm will depend on the height of the water, the speed of the current, the physical state of the person and the environment (existence of a refuge zone, for example). For the same hazard, the human risk may be high, the economic impact will be high, but for the building the risk will be low (with little risk of structural damage). The risk will thus not be assessed in the same way depending on the cause of submergence (storm, cyclone or tsunami).

Coastline retreat generally involvers relatively little risk for humans provided a prevention and warning system is in place, whereas for infrastructure and buildings, the risks are much greater and are often irreversible. In this case too, prevention remains the best approach, especially anticipation and relocation (so-called 'strategic withdrawal').

Adaptation to climate change

In some regions of the world, climate change will have significant effects on storm trajectories, and it will change the offshore wind, wave and current regimes that affect the shoreline. Nevertheless, particularly in metropolitan France, the most important effects will be linked to the rise in sea level, which will exacerbate both coastal flooding and erosion, thereby increasing coastline retreat. Some of the consequences of climate change cannot be avoided: the frequency of submersion during storms will increase mechanically because a rise in sea level of at least 20 to 30 cm is now inevitable in the 21st century. However, if greenhouse gas emissions remain unabated, the rise in sea level will reach 50 cm to 1 m and possibly more, in 2100. Under these conditions, and despite all the uncertainties of coastal modeling at these time scales, the consequences for the coastline retreat will be very important.

The adaptation of society to these changes can be summarized in several complementary attitudes, ranging from defense, with the construction of defense structures and facilities, to strategic retreat, to the restoration of spaces available for sedimentary mobility and biodiversity. Adaptation can be limited by environmental, technological, economic, financial or social constraints, which vary according to the local context. For example, the protection of major cities, such as Malé in the Maldives and New York in the United States, whatever the cost, seems inevitable, even if these cities are particularly vulnerable to sea-level rise. On the other hand, environmental and financial constraints will increasingly lead to considering the relocation option for many peri-urban and rural sites, including those located along the coasts of metropolitan and overseas France.

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6. Will atoll reef islands disappear under climate change?

Virginie Duvat

Atoll countries like the Maldives (374,000), Tuvalu (11,000) and Kiribati (110,000 inhabitants) are made up of atoll reef islands, *i.e.* small low-lying islands (< 4 m in altitude and < 1 km²) made of coral deposits that consitute the only inhabitable land. These countries are at the forefront of the impacts of climate change, and are widely considered to be under the threat of disappearance in the coming decades as a result of sea-level rise and of the rapid degradation of their vital resources, which are very sensitive to ocean warming and acidification. Marginalized on the international stage a decade ago, these countries recently formed a pressure group capable of influencing international decisions, such as the signing of the Paris Agreement at COP 21, where they obtained agreement on maintaining the global increase in temperature below 1.5 °C by 2100. Widespread discourse about their rapid future disappearance, by their heads of state, by NGOs and researchers worried about the rapid degradation of coral reefs, was recognized from the 1990s on, and finally generally accepted in the 2000s. It was not until 2010 that after studying the response of reef islands to accelerated sea-level rise, geomorphologists questioned the truth of this discourse. What do we know today? Will France, which includes the largest group of atolls (77) in the world with the Tuamotu, lose thousands of islands, and will Tahiti have to accommodate the 15,000 inhabitants of this archipelago?

Recent changes in atoll reef island area

In order to evaluate the risk of disappearance of atoll reef islands, researchers use multi-date image analysis, which enables assessment of the changes in island land area. Historical aerial photographs taken in between 1940 and the 1960s are generally the oldest source of information available, making it possible to document changes in island area over the past 50 to 70 years. As a result, we currently have data on about 400 Pacific islands (Marshall, Kiribati, Tuvalu, Federated States of Micronesia, Tuamotu...), and 200 islands in the Indian Ocean (Maldives and Chagos). The results obtained for Pacific reef islands are unanimous: these islands have not undergone widespread contraction in the last 50 to 100 years that would confirm the probability of their disappearance in the coming decades. Seventy-three percent of the islands in the sample remained stable in area, 19% expanded and 8% contracted. Data from 134 Tuamotu Islands produced similar results: 43% remained stable in area, 39% expanded and 18% contracted (Fig. 1). On the other hand, over the same period, in the Maldives, 44% of the islands of the Huvadhoo Atoll lost land area, 37.5% remained stable and 18.5% increased in size. Are these differences due to differences in the rate of sea-level rise or to other factors?

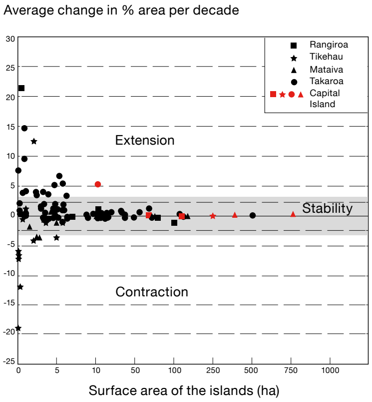

Fig. 1 – The French atoll reef islands of the Tuamotu Archipelago are not threatened by disappearance. The gray band represents the area of uncertainty (+/- 3%). As this graph shows, the most populated islands of the atolls have either remained stable or expanded in area since the 1960s. According to DUVAT *et al.*, in press. ■

Explaining the contrasting responses of reef islands between archipelagos

The responses of reef islands to climate-related pressures vary depending on the size of the island, the largest islands being the most stable in area. Huvadhoo Atoll, which is made up of very small islands, is therefore more likely to be subject to high variations in island land area over short time periods than the Pacific atolls, which are generally made up of larger islands. Because the island communities generally settled the largest islands, including on Huvadhoo Atoll, they are not directly threatened by potential island destabilization at the present time. Moreover, no correlation was found between the rate of sea-level rise and changes in island land area. For example, the high rate of sea-level rise observed in Tuvalu (+ 30 cm since 1950) has not caused island contraction at this time. On the other hand, while nearly half the islands in the Huvadhoo Atoll have contracted over the past 50-60 years, sea-level rise there has only been 7 cm since 1950. Other factors, such as the production of sediment by coral reefs, the impact of storms and anthropogenic disturbances, also determine changes in island area. While coral reefs are heavily degraded in the capital atolls that concentrate the majority of the population, degradation is localized and affects only a limited number of islands at the scale of entire archipelagos, making anthropogenic disturbances imperceptible in statistical terms. In addition, the reduction of sediment inputs on inhabited islands is offset by artificial land area gains due to land reclamation. In a sample of 107 Tuamotu islands, only 42.4% evolved naturally versus 57.6% on which changes in land area have been at least partly driven by anthropogenic factors. In 26% of the cases, human activities are the main factor controlling island change (land reclamation, sediment mining, coastline fixing...). Therefore, two questions arise: from what point in time and how will the impact of rising sea levels be manifested? How are anthropogenic factors likely to influence future changes in reef island areas? Accelerated sea-level rise, combined with ocean warming and acidification, both of which are detrimental to coral health, will, beyond a certain threshold (still unknown), negatively affect reef islands. When corals die and the reef is eroded by waves, reef islands will no longer be fed with fresh sediments. In such contexts, significant wave height will increase, and will in turn, increase the erosive impact of storm waves and the frequency of marine inundation. The depopulation of reef islands is likely to begin at that time. On the other hand, in locations where coral reefs remain healthy, keep up with sea-level rise and keep providing the islands with sediments, these islands will survive. But, and this is the link with the second question posed above, the natural capacity of reef islands to keep adjusting to sea-level rise as a result of sediment supply by the reef ecosystem (Fig. 2) can only function on natural coasts where no human construction obstructs sediment deposition. Islands whose coasts are settled are condemned in the long term unless human societies change their developmental standards, *i.e.*, reconstruct existing buildings on stilts so as not to interfere with the sediment fluxes that are essential to the natural vertical adjustment of islands to sea-level rise.

Fig. 2 – **The reef islands of Rangiroa Atoll, Tuamotu archipelago, French Polynesia, in the Blue Lagoon area.** These natural islands are abundantly supplied with sediments by the reef ecosystem, as shown by sediment deposits covering the reef flat. Such islands have the ability to adjust to rising sea levels. © V. DUVAT. ■

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7. Climate change and marine biodiversity

Grégory Beaugrand

Scientific evidence is mounting concerning the penetration of global warming into the oceans. Observations indicate that over 90% of warming in the global system has taken place in the oceans. Many results already show that this temperature increase is causing adaptive, behavioural, physiological, phenological and biogeographical responses among marine organisms.

Species displacement, invasion and disappearance

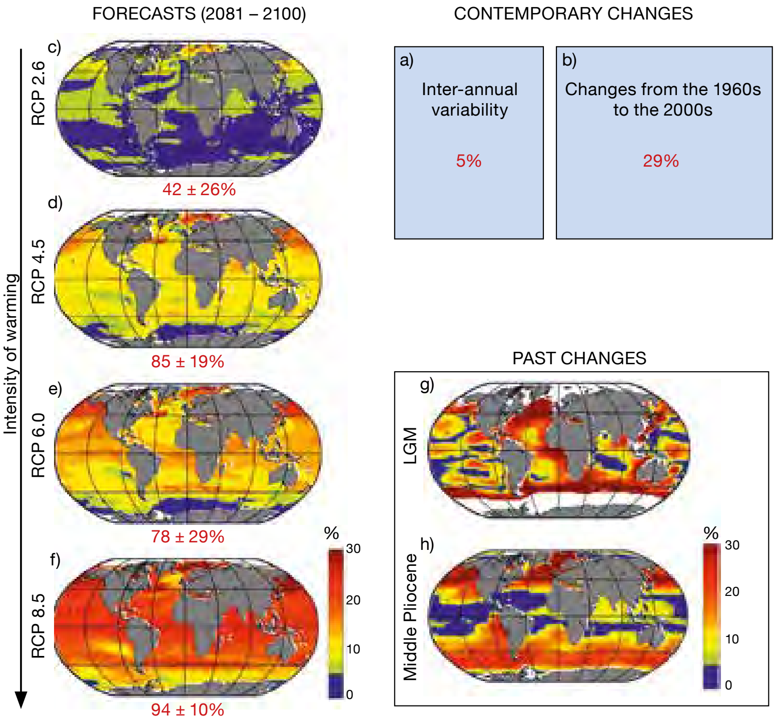
One of the first expected consequences of climate change for marine organisms is the horizontal displacement of species towards the poles. This phenomenon has been clearly detected along the European coasts. Zooplankton species characterizing temperate and warm temperate waters have migrated northwards. A group of species formerly present only in the Bay of Biscay has now been identified as far off as the west of the Norwegian coasts. This represents a biogeographical movement of almost 1000 km in around twenty years. Meanwhile, species that are characteristic of cooler water masses have declined. It is not just planktonic ecosystems that have undergone profound modifications in their biodiversity. Many studies have reported the appearance of new species of tropical fish in the Bay of Biscay, and their progressive migration along the European continental slope. Researchers analysed the long-term changes in the spatial distribution of 90 fish species in the North Sea. During the period studied (1977 to 2001), the average temperature rise of the North Sea was barely 1.05°C. However, of the 36 fish species whose northern or southern distribution boundary was in the North Sea, 15 species (including common sole and Atlantic cod) had migrated in response to the increased water temperature. Moreover, climatologists predict a temperature increase of 1 to 2.5°C by 2050. If such values are reached, sole and cod would probably disappear from this region, with many potential economic consequences. Along the French coasts, laminaria, scallops and whelks could even disappear before the end of the century, if the high intensity of the warming continues.

Substantial biodiversity changes expected

There have been few studies on the expected consequences of global warming for biodiversity on large spatial scales. The main reason for this is that oceanographers have very limited knowledge about the composition of marine biodiversity, since 90% of species have not yet been described (cf. III.17). Also responsible is the lack of information on the biology, biogeography and ecology of many species. Based on a new macro-ecological theory about the organization of life in the oceans (the METAL theory), a CNRS study reconstructed the contemporary biodiversity of the superficial ocean (the top 200 m of the water column). For the first time, it allowed us to estimate the vulnerability of biodiversity in the face of global warming. The major changes in biodiversity from the 1960s to the 2000s were around six times more widespread in the global ocean (29% of the total area of the oceans) than the changes observed due to natural variability (average biodiversity variability from one year to the next: 5% of the total area of the oceans), during the 1960-2013 period (Fig.). The expected biodiversity changes from now to the end of the century have also been estimated using four climate scenarios and five models of general ocean-atmosphere circulation. If warming remains below a 2°C global increase, 42% of the area of the oceans will undergo substantial biodiversity changes. If it exceeds 2°C, the changes will affect 78 to 94% of the area of the ocean.

For the purposes of comparison, past biodiversity was reconstructed for two periods: the Last Glacial Maximum and the Middle Pliocene. This reconstruction showed that the expected biodiversity changes by the end of the century could be of the same magnitude as those seen from the Last Glacial Maximum or the Middle Pliocene to the present day.

For all the global warming models and intensities, the global increase in temperatures and the resulting regional hydro-climatic changes would cause a biodiversity decrease in the warm regions of the ocean (permanently stratified regions), whereas biodiversity would increase in the cold regions. The rates of increase would probably be very high in the polar regions. This theoretical result has been observed in certain extratropical regions, for crustaceans and fish. It is important to note that the increasing biodiversity will not compensate for species disappearance, because it will simply be the result of a reorganization of species and communities on a global scale.



Vulnerability of marine biodiversity in the face of past, contemporary and current climate changes. a) Vulnerability of biodiversity connected to intra-annual fluctuations of sea surface temperatures. b) Vulnerability of biodiversity connected to temperature changes from the 1960s to the 2000s. c-f) Biodiversity changes from 2081 to 2100, and from 2006 to 2013, corresponding to different warming intensities. g) Vulnerability of biodiversity connected to temperature changes between the Last Glacial Maximum and the 1960s. h) Vulnerability of biodiversity connected to surface temperature changes between the Middle Pliocene and the 1960s. These changes, based on quantitative assessments, are expressed here in percentages. According to BEAUGRAND *et al.*, 2015. ■

Impacts on ecosystem services

All of these biodiversity modifications will be accompanied by significant changes in terms of ecosystem services. Each year, the ecosystem services of regulation and supply provide 15 to 51 trillion euros, and marine biodiversity allows the exploitation of 80 million tonnes of fish and marine invertebrates. The biodiversity changes will cause a global reorganization of species in the ocean, including exploited species (by fishing and aquaculture), those which are potentially dangerous to humans (jellyfish and other planktonic organisms, toxic or deadly crabs, dangerous fish) and beneficial species (for food supplements and medication). The regulation services will be disturbed, and other studies suggest that biodiversity modifications could also affect certain biogeochemical cycles, in particular the oceanic carbon pump, which could decline in a warmer world (cf. II.14).

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8. Biodiversity and globalization: biological introductions

Frédérique Viard

Natural species ranges evolve in response to environmental changes (cf. VI.7). They are also dramatically and rapidly modified due to the translocation of organisms outside their native range by human activities, *i.e.* biological introduction processes. If today the Asian brown seaweed, Sargassum muticum, extends along the coast of America from Mexico to Alaska, and in Europe from Morocco to Norway, it is due to its accidental transportation by humans since the early 1940s. Similarly, the current distribution of the oyster Crassostrea gigas (recently renamed Magallana gigas), also of Asian origin, in both hemispheres of the Atlantic and Pacific oceans is largely a result of its deliberate introduction since the late 19th century. Their current distribution far exceeds the natural dispersal capacities of these species and now covers distant and disjointed biogeographic provinces (Fig. 1).

A continuous wave mirroring trade globalization

Human activities are responsible for the introduction of a large number of species in the marine environment, estimated at about 1,400 species in European seas. Although these biological introductions have taken place since mankind started travelling around the globe, they have greatly accelerated since the end of the 19th century, particularly in connection with a particular technological innovation: the invention of steel vessels (cf. IV.9). Unlike wooden vessels, these vessels are equipped with ballasts filled with seawater that can transport many species' propagules. A study of 550 vessels showed that their ballasts contained more than 1,000 species. The growth in such introductions increased further in the 20th century, with the globalization of aquaculture and maritime trade. Thus, the number of non-native species in the seas of Western Europe increased by 173% between 1970 and 2013. In the Mediterranean Sea, where the Suez Canal is an additional vector of introduction, the increase reached 204% over the same period (Fig. 2).

These biological introductions raise questions for ecologists and evolutionary biologists: how to explain the success of these species in an environment in which they did not evolve? Concerning the marine environment, one of the explanations proposed is their increasing artificialization. As two thirds of the world's population live within 80 km of the coast, the construction of artificial coastal infrastructures (ports, offshore platforms, dams to protect against erosion...) has

Fig. 1 – **Two iconic marine species introduced in Europe: Magallana gigas oysters (left) widely grown and consumed in France, and the brown seaweed Sargassum muticum (right), here growing on a seagrass bed in Brittany.** © Y. FONTANA (left) / L. LÉVÊQUE (right) – Roscoff Biological Station. ■

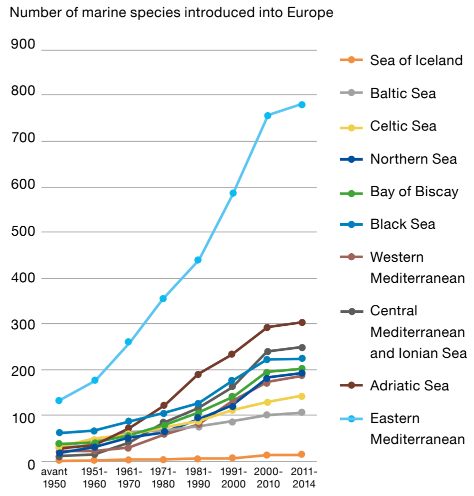

Fig. 2 – **Increase in the number of marine species introduced after the middle of the 20th century in various European seas.** Source: European Environment Agency. ■

increased. These new habitats are largely colonized by introduced species. In some taxonomic groups, they represent 30% of the species present in marinas, whereas in their natural habitats, these introduced species represent less than 1%. This is not surprising given that commercial and recreational harbors are hotspots of introduction and bridgeheads for the expansion of introduced species. Moreover, their particular characteristics (pollution, substrates, cf. VI.16) could reduce the competitive advantage of local species and facilitate the installation of the introduced ones. A second major reason for the success of species introduced into the marine environment is propagule pressure (related to the number of introduced propagules and the number of introduction events). Genetic studies have shown that in the vast majority of cases (76% of introduced species in Europe for which data exist), populations are genetically highly diverse. This observation highlights repeated introductions of multiple origins, and by various introduction vectors (aquariology, nautical recreation, research, offshore platforms… in addition to maritime traffic and aquaculture) of a very large number of individuals. Moreover, the presence of a microscopic pelagic life stage in many marine species (70 to 80% of the invertebrates), easily transported in the ballast water of thousands of ships traveling the world, accentuates this propagule pressure.

Shuffling the biodiversity at global scale

The consequences of these biological introductions are multiple and often accompanied by cascading effects. In a recent pan-European study of about a hundred introduced species in Europe, a group of researchers showed that 29 species appear to have no effects, but that 81 modify the biodiversity, structure or functioning of ecosystems. While in some cases, they cause local increases in biodiversity, in other cases, on the contrary, they reduce biodiversity. These species also influence ecosystem services, again with antagonistic effects depending on the species: some represent new economic resources, while others compete with exploited species. On a global scale, they contribute to the homogenization of biological diversity. Although researchers are beginning to understand the processes that facilitate the introduction of these species, many questions remain. For example, why, after a latent phase, do some of these species begin to proliferate, or, on the contrary, why do some introduced species that were previously invasive suddenly regress? Many questions remain as to their long-term evolution. By modifying distribution areas on a transoceanic scale, the introduction of species also requires redefining biogeographic boundaries. They also act in synergy with other pillars of global change (such as resource exploitation and climate change). Whether their effects are assessed as positive or negative, and whatever the lively debate about their management, introduced species are undeniably new actors of biodiversity and of the evolution of marine ecosystems.

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9. The vulnerabilities of the deep ocean's ecosystems

Nadine Le Bris

The ocean's deep waters play a major role in alleviating the effects of global warming by storing a large proportion of the CO_2 produced by human activities and by absorbing the heat accumulated through the greenhouse effect. Today, an increase in dissolved CO_2 and in temperature has already been evidenced at a depth of more than 1,000 m in some ocean regions: the first signs that the disturbance already affects the entire water column.

Climate model projections predict that many deep-sea ecosystems rich in biodiversity and biomass will be exposed to disturbance by 2100. If these trends are confirmed, major changes in the functioning and services provided by these ecosystems are to be expected (cf. V.3). However, it is difficult to foresee the consequences without knowledge of natural fluctuations of these environments. Long-term observations are rare in the deep seabed, even relatively close to the coast, *i.e.* on continental margins or the surroundings of oceanic archipelagos – where numerous topographic features, such as canyons and seamounts, are key habitats for the conservation of exploited species. However, major risk factors can already be identified from our knowledge of mechanisms of interaction between marine species and their environment, along with a number of pioneer studies.

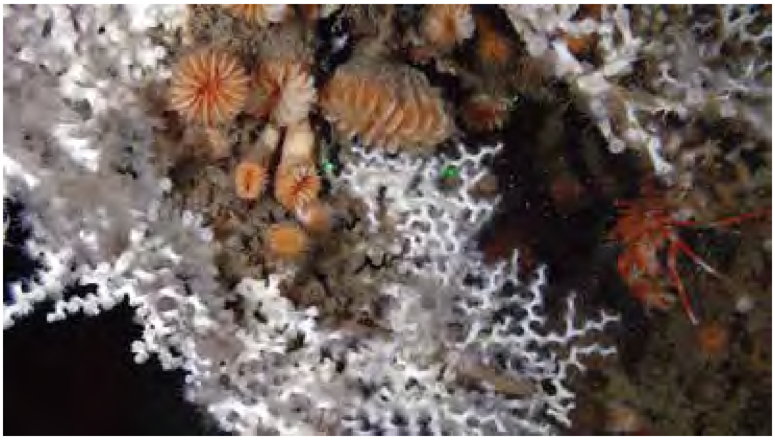

Fig. 1 – **Coral assemblage at a depth of 500 meters in the Mediterranean Sea. © UPMC / LECOB.** ■

Warming and deoxygenation

The first of these threats is deoxygenation, amplified by ocean warming, which naturally affects intermediate waters (from a few hundred to about 1,000 meters deep) by reducing their 'ventilation'. Indeed, the warmer the surface water, the less it absorbs oxygen and the less it mixes with deep waters. Large areas of the tropical ocean - particularly the highly productive regions of the northern Indian Ocean, the west coasts of the American continent and West Africa – already encompass intermediate waters devoid of oxygen. Since the 1960s, these regions have lost more than 4% of their oxygen every 10 years and have expanded considerably. Many mobile species, including tuna or billfish, avoid these 'anoxic zones' and the seabed of these 'dead zones' only hosts microorganisms – with the exception of rare animal species on the fringes, where oxygen is still available. While reducing and fragmenting the habitable space of many marine species, these oxygen-depleted waters promote proliferation of predators that can survive low-oxygen conditions, such as Humbolt's squid, and consequently affect the whole ecosystem.

More subtle changes in water temperature can have equally dramatic consequences for ecosystems. The increase of a tenth of degree every 10 years in some polar regions gradually allows predatory crabs to expand their territory and to decimate species previously protected by very cold water (-1.5°C). In the Mediterranean Sea, warming raises the risk of irreversible damage to deep-sea coral reefs (Fig. 1), whose habitat's thermal limit is less than 1°C above the deep-water temperature (13.5-14°C) of this semi-enclosed basin.

Acidification

In other areas, including the Gulf of Mexico, questions arise concerning degradation of the deep-sea reef on which many fish and crustacean species depend, due to the combination of acidification and deoxygenation. Deep-sea water is naturally more acidic than surface water. Carbon dioxide consumption by photosynthesis is no longer possible in the dark and, instead, deep layers are gradually enriched in CO_2 through the microbial degradation of sinking organic matter (*i.e.* remineralization). As a result, deep-sea corals are generally closer to the threshold of corrosive waters promoting carbonate dissolution than their tropical counterparts. While aquarium experiments revealed their adaptability to the high CO_2 levels mimicking the most pessimistic scenarios, the energy demand to form a calcium carbonate skeleton in such conditions is high. Associated with oxygen, nutritional conditions are another factor of vulnerability that is dependent on global change, and it is therefore difficult to extrapolate the response of deep-sea corals to water acidification without a better knowledge of their environmental conditions.

Deprived of light, most deep ecosystems are closely connected to surface water, where the organic matter that feeds them derives from photosynthesis. Rapid changes in the quantity and quality of these nutrients have already been reported, down to depths of several thousand meters on abyssal plains. Do they reflect extreme 'natural' events or global disturbance? Observation series covering 15 to 25 years are still too short to conclude, but they confirm that in-depth biodiversity changes very rapidly as resources become available.

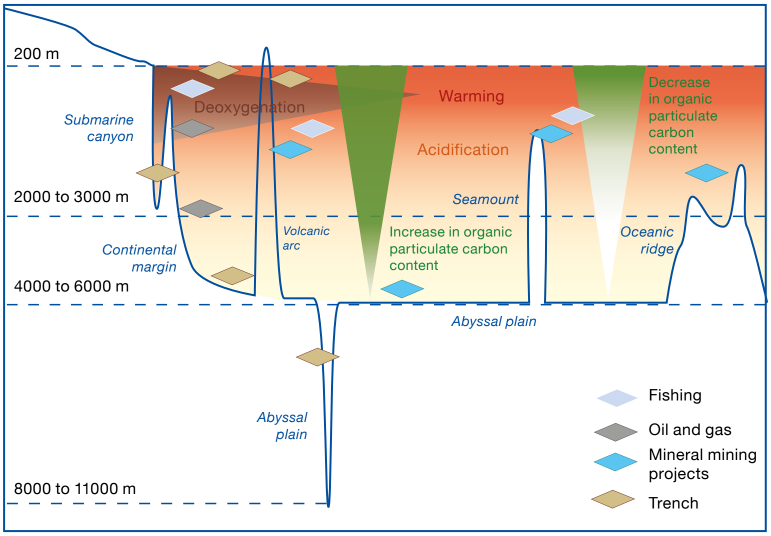

Fig. 2 – **Schematic diagram illustrating the combined pressures of human activities on various ecosystems at great depths.** Adapted from LEVIN and LE BRIS, 2015. ■

Maintaining ecosystem integrity

The rapid response of deep-sea biodiversity to changes calls for early consideration of such risks in order not to compromise the mitigation ability of ocean-induced climate disturbance and many other ecological functions guaranteed by the biodiversity of the ocean floor. Maintaining the integrity of deep-sea ecosystems under climate change is even more critical, as the exploitation of mineral, energetic or biological resources is rapidly expanding in deep waters, and it is extremely important to ensure that the environmental impacts of these activities are both controlled and minimized (Fig. 2). A significant effort is therefore needed to increase our knowledge of the sensitivity of deep-sea species and the synergistic effects that could affect other ecosystems, including those of the ocean's surface. However, we must admit that today, we only have a very limited view of the disturbances to be expected for these ecosystems. Deep sea ecology is a young science. Only 175 years ago, scientists considered marine life below a depth of 500 meters to be impossible. In this context, Marine Protected Areas are of great value, especially those that extend offshore. While integrating and protecting the most vulnerable components of these ecosystems, they constitute natural laboratories to better understand the effects of climate change at great depth and to ensure long-term surveillance of their consequences.

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10. Environmental and health impacts of toxic microalgae

Zouher Amzil

Microalgae are the basis of food chains in marine ecosystems. They are mainly composed of unicellular pelagic and benthic photosynthetic organisms. When environmental conditions are favorable, microalgae species may proliferate temporarily at high densities. Factors that influence their development include hydrographic, meteorological and nutritional processes. At the global level, an increasing number of regions have been affected by toxic or harmful microalgae blooms for several decades (cf. VI.11). High cellular concentrations may give rise to efflorescence visible in the red color of the surface water. These excessive blooms can have adverse effects on marine organisms (mortality, impaired reproduction) or on human health, through direct exposure or as a result of bioaccumulation of algal toxins in seafood. Marine mammals can also be victims of bio-accumulated algal toxins along the trophic chain to their prey (Fig. 1).

Red arrows indicate the pathways through which toxins pass, *via* (left) and benthic (right) trophic-pelagic networks

Fig. 1 – **Risk of accumulation of microalgae toxins in various marine organisms along the food chain.** Source: www.whoi.edu/redtide/impacts/ecosystems. ■

Increasing proliferation

There is increasing evidence that there has been an intensification of such phytoplankton-related events over the past 30 years, either as a geographical extension of toxic episodes or as an increase on the diversity of toxic species and toxic metabolites. Of the tens of thousands of microalgae species known to date, more than 200 are thought to have harmful effects, while about one hundred species produce toxins. The latter are classified in different categories: non-toxic microalgae, but capable of reaching high concentrations, which can lead to the death of marine fauna by anoxia; microalgae that synthesize toxins which can accumulate in the food chain and may poison the consumer; microalgae which are toxic to fish and other marine organisms *via* the production of hemolytic toxins; toxic microalgae that have an impact on health through inhalation or contact with the skin.

Several decades ago, few countries were affected by blooms of toxic microalgae, but today coastal regions around the world are affected by the unprecedented variety and frequency of proliferation. For example, the figure 2 shows the worldwide distribution of the occurrence of paralytic shellfish poisoning (PSP)

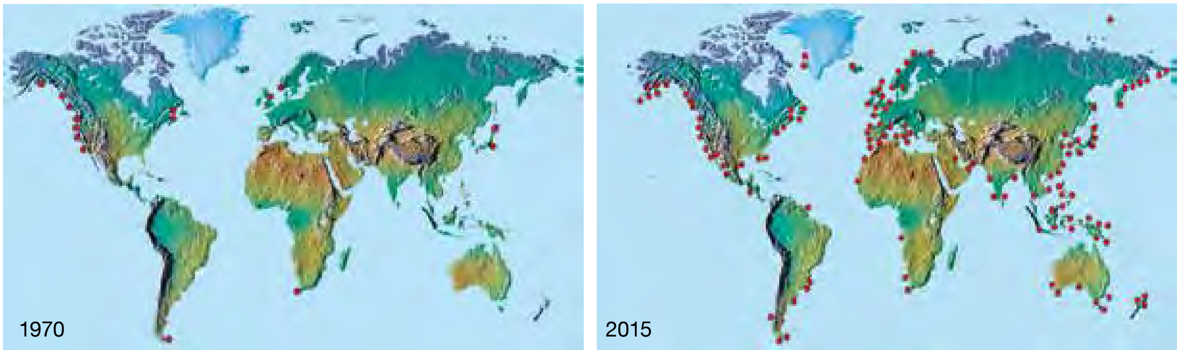

Fig. 2 – **Worldwide distribution of the occurrence of paralytic shellfish poisoning (PSP) associated with toxic microalgae blooms observed in 1970 and 2015.** Source: Woods Hole Oceanographic Institution, USA, 2007. ■

associated with toxic microalgae blooms observed in 1970 and 2015. In 1970, toxin-producing species were found only in the coastal seas of temperate Europe, North America and Japan. In 2015, these species were observed in the same regions, but also on the Pacific coast of Russia.

Extension of toxic episodes

Microalgae toxins are secondary metabolites that exhibit a variety of compounds with varying chemical structures and whose action depends on different toxicity mechanisms. Some lead to diarrhea, amnesia or neurotoxic troubles. In addition, over the last 40 years, toxic episodes have multiplied: diarrheic, amnesic and azaspiracid poisoning by shellfish, damage to health by inhalation or through contact with the skin. The causes of this increase range from natural mechanisms that cause the dispersal of microalgae species, to a multitude of anthropogenic phenomena, including pollution, climate change, an increase in surveillance, the development of detection tools that make it easier to detect proliferations, and international research. In some parts of the world, it is increasingly clear that chronic eutrophication due to the discharge of urban, agricultural and industrial waste promotes the development of toxic microalgae. Ballast water from ships may be a potential vector for the dispersal of non-native species, as spores and toxic microalgae cysts can survive during transport. Similarly, the transfer of live bivalve molluscs from one production area to another is also a potential vector for the geographical dispersion of viable cysts of toxic species.

Climate change also has an impact on the proliferation of toxic microalgae, and oceans, which act as heat reservoirs, and respond to this change by thermohaline circulation which puts nutrients, oxygen and CO_2 in motion. Global warming will lead marine organisms to adapt to changes including a rise in temperature, strong stratification, photosynthesis stimulation by elevated CO_2 levels and changes in coastal inputs and nutrient availability.

Monitoring networks

The risks posed by toxic and harmful microalgae have led to the creation of networks and the monitoring of health thresholds when sufficient toxicological data are available. When these thresholds are reached or exceeded in seafood meat, shellfish production or recreational fishing areas are closed and the sale of the shellfish concerned is prohibited. These closures have a direct impact on the profession, leading to economic losses, but also indirectly, by conveying a negative image of the sector to consumers and mass retailers.

Considerable advances in monitoring systems have been made over the past 12 years to optimize the prediction of toxic algae efflorescence and their impact on seafood safety. Through long-term series of observations at the global scale, today, there is a scientific consensus on the significant increase in toxic algal blooms in recent decades, as well as in the number of toxins and vector species.

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11. Marine eutrophication

Alain Ménesguen

Manifestations

Like in freshwater, some phytoplankton species, suspended in water, can proliferate in a few days, causing unusual coloring of the sea. The frequency of these 'colored waters' in lagoons and in the coastal sea increased in the second half of the twentieth century, particularly near the industrialized world (North America, West Europe, Japan, China...). The different colors are caused by different genera. Dark green waters are usually caused by siliceous diatomaceous diatoms. White and foamy waters are caused by colonial flagellates *Phaeocystis* in April in the North Sea. Yellow-green waters are caused by dinoflagellate *Lepidodinium* in summer in southern Brittany (Fig.) and Vendée. In late spring, spectacular red tides (Australia, Brazil) are caused by the predatory dinoflagellate *Noctiluca* . Among marine macroalgae that colonize the coastal seabed, green *Cladophora algae* (filaments), Ulva and Ulvaria (blades), brown *Ectocarpus* and *Pylaiella* algae (branched filaments) as well as red *Gracilaria* algae, once detached, are able to survive and multiply through cuttings, and are then confined to places with sufficient light and that are rich in nutrients. Accumulations of green algae gained global media visibility in the Venice lagoon (500 000 tons in 1990), in Brittany bays (100 000 tons) and in Qingdao, China (1 million tons since 2008). Since 2010, floating brown macroalgae (*Sargassum* genus) have also invaded the coasts of the Caribbean islands. Their natural oceanic proliferation may have intensified since part of the Amazon rainforest has been cultivated for agricultural purposes, resulting in increased supplies of nutrients to the Central Atlantic.

The accumulated biomass quickly exceeds the consumption capacity of local filterers or grazers, and a large amount of organic matter consequently settles on the seabed. Its bacterial degradation, initially aerobic, consumes dissolved oxygen in the bottom waters. As it becomes anoxic and hence fatal to wildlife, the environment favors the development of anaerobic bacteria that use sulfates as oxidants and release hydrogen sulfide gas, which is also fatal to the animal world as soon as it accumulates in the environment. Sites with annual phytoplankton blooms have experienced severe mortalities of marine fauna (Gulf of Mexico, Chesapeake Bay in the United States, northern Adriatic Sea, Inland Sea of Japan), and even the disappearance of wildlife following long anoxic

Green dinoflagellate water in summer, *Lepidodinium chlorophorum*. © Minyvel / Le Médec, 01/08/2014, Préfailles, Loire-Atlantique. ■

periods ('dead zones' in the Gulf of Mexico, Baltic Sea and Black Sea). Coastal sites with 'green or brown tides' are dangerous for local residents when the algae rot in deposits, thereby producing hydrogen sulfide.

To these quantitative nuisances must be added qualitative nuisances, due to the modification of the relationships between chemical elements in marine water. Nitrogen enrichment, relative to constant phosphorus or silicon, can promote non-siliceous phytoplankton (dinoflagellates including toxic), or stimulate the production of toxins by certain diatoms (such as *Pseudo-nitzschia australis*).

Finally, marine eutrophication is a nuisance created by the accumulation of an algal biomass far beyond the evacuation and digestion capacities of the local ecosystem. This accumulation disrupts the food chain, in particular through the oxygen rarefaction it induces near the seabed, until the death of the fauna by asphyxiation. Eutrophication also modifies algal and faunal biodiversity, as well as the toxicity caused by certain microalgae.

Mechanisms

For the eutrophication phenomena to take place, at least three conditions must be fulfilled: good illumination of the water layer (for photosynthesis); high nutrient richness (nitrogen, phosphorus); sufficient confinement of waters (static: semi-enclosed lagoons, horizontal dynamics: zones of low drift in the open sea, and/or vertical dynamics: saline or thermal stratification of the water column). The first factor limits the eutrophication to shallow or non-turbid surface waters. As marine surface waters are naturally poor in nutrients, the second factor limited 'natural' cases of eutrophication in some deep-sea oceanic upwelling areas (such as off Namibia) until the 20th century. However, the very high increase in nutrient inputs from urban discharges, and especially leaching from highly fertilized agricultural land, has enabled eutrophication in river dilution plumes. The third factor explains why only lagoons, enclosed seas or confined bays have developed eutrophication when their waters have been enriched.

Monitoring and remediation

Due to its serious impact on marine ecosystems and their human exploitation (loss of shellfish and fish yield, prohibition of shellfish sale due to their toxicity), eutrophication is now being monitored. Monitoring is based on networks of coastal stations that measure variations in nutrient richness (nitrogen and phosphorus), algal biomass, the abundance of toxic species and the oxygen content of bottom waters. The eutrophication indicators deduced from these measurements are compared with critical thresholds, of which there are unfortunately no universally accepted values. In north-western Europe, the classification of marine areas varies according to the criteria adopted by the OSPAR Convention, the DCE or DCSMM Directives. In the United States, the grid of the Assessment of Estuarine Trophic Status is used. Monitoring reveals very slow changes in eutrophic ecosystems, but makes it possible to adapt the objectives of reducing of nitrogen nutrients and phosphorus inputs by rivers. Measurements of surface phytoplankton biomass have been generalized to all oceans thanks to satellite sensors. High-frequency measurements (at 15 minute intervals) of nutrients, biomass and dissolved oxygen are increasing thanks to instrumented buoys.

Eutrophication can be controlled by reducing the level of one of the three determining factors. The reduction in light reduced the biomass of *Ulva* in Venice when dredging for Philippine clams expanded. Reducing the confinement of the Tunis lagoon required massive works to ensure movement of the water. Concerning nutrients, phosphorus has already been reduced because of the important role it plays in causing fresh water eutrophication, this leaves nitrogen, which is in great excess compared to the 'natural' situation. Modeling of the most eutrophic ecosystems (Gulf of Mexico, Baltic Sea, North Sea) has already frequently shown that a reduction of more than 50% of current nitrogen inputs is needed to reduce this nuisance. This implies a profound change in agricultural practices.

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12. Chemical pollution of oceans

Thierry Burgeot

The United Nations Environment Program (UNEP) estimates that mismanagement of chemicals, from production to waste treatment, is responsible for $236 billion in losses worldwide. Of the 140,000 chemicals marketed today, only a fraction has actually been evaluated to determine the effects of chemical pollution on health and the environment. Of the 140,000 substances listed by ECHA (2015), 30,000 are subject to the European REACH marketing regulations, 5000 are characterized for their highest volume of production by the OECD (2009) and 4000 are identified as carcinogenic.

Transportation and bioaccumulation

Chemical contaminants transit to the marine environment through inland waterways, winds, low air, rainfall, or are directly released into the oceans. Some can be transported through the atmosphere very long distances from their source. Chemical contaminants add to the multiple sources of human activity that exert spatial and temporal pressure on the globe. In offshore areas, chemical contamination is lower than the concentrations encountered in coastal areas. However, offshore areas can be impacted by specific contamination, such as polycyclic aromatic hydrocarbons and alkylphenols around oil platforms in the North Sea. Traces of pesticides have been found in the main traffic lanes of merchant ships in the North Sea (a few nanograms per liter); and in the Mariana pit, high concentrations of polychlorobyphenyls are bioaccumulated by amphipods living in the 11,000 meter deep Mariana trench. The fate of these contaminants in water, sediment and in organisms is a major factor in the risk of chemical exposure.

Diversification of chemical contamination

Sources of inputs into the ocean have multiplied due to changes in the industrial production of chemicals, agricultural practices, together with the dissemination of urban, pharmaceutical and domestic waste. Future projections (Fig. 1) suggest chemical contaminants will be multiplied by a factor of 4.3 by 2050.

Historical monitoring of contaminants, including heavy metals, persistent organic compounds, ammunition deposits and radioactive waste, has been expanded to emerging contaminants including nanoparticles, microplastics, pharmaceuticals, antibiotics and illicit drugs, hygiene, phytosanitary, biocides, food additives, anti-fouling paints, endocrine disruptors, flame retardants, fluorinated compounds and rare earth compounds.

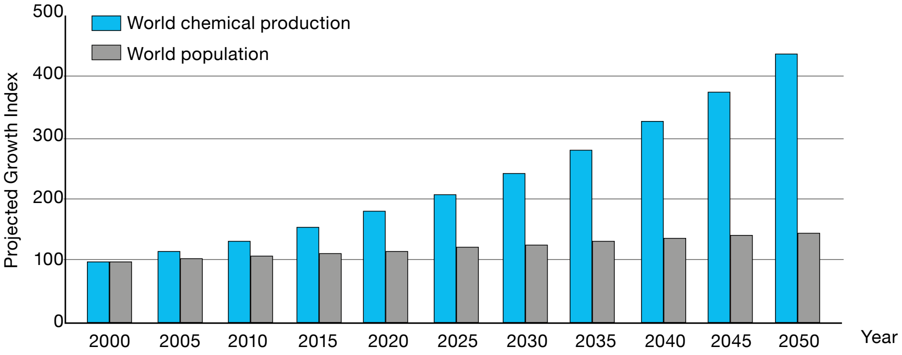

Fig. 1 – **Projection of global chemical contamination following an increase of 3% per year, faster than the world population growth, estimated at 0.77% per year.** Source: M. P. WILSON and M. R. SCHWARZMAN, 2009. ■

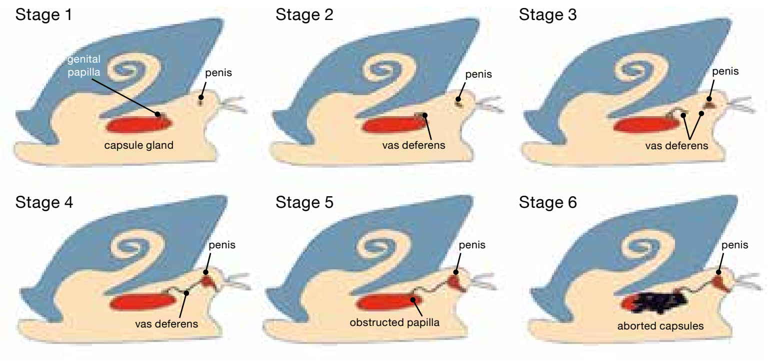

Fig. 2 – **Illustration of female Nucelle in intersex stages, by imposex measuring on the Normandy coast.** Source: E. POISSON *et al.*, 2011. ■

Impact of chemical contamination

Chemical contaminants present in seawater or in sediments enter organisms *via* the food chain or through direct contact with water and sediment. The contaminants evolve from the bottom to the top of the trophic chain by bioaccumulation and biotransformation within the tissues and organs of the organisms. Chemical contaminants are mainly assimilated by the cells of the organism that metabolize them. The metabolites are then eliminated, but in the case of exposure to chronic contamination throughout the life cycle, they can cause biochemical and cellular alterations or damage DNA. These early effects cause alterations in major physiological functions, such as reproduction, growth and immune defenses. All organisms in the food chain can be impacted. Biological mechanisms are impacted differently depending on the chemical properties and toxicity of the family of contaminants. For example, pesticides can disrupt photosynthesis mechanisms and the growth of microalgae. Endocrine disruptors are responsible for the emergence of intersex fish and bivalves. The most emblematic case of the marine environment is probably the appearance of a penis in gastropod females (Nucella lapilus) exposed to TBT (biocide used as antifouling), used to paint ship hulls. Classification of the physiological impact according to stages from 1 to 6 makes it possible to characterize increasing alteration (Fig. 2) of this intersex character called ‘imposex’. Other disturbances resulting from medium- and long-term exposure appear, such as early stages of cancer in flatfish, for example in flounders caught in the Seine estuary, in France. Large mammals are not spared and polar bears (Ursus maritimus) exposed to mercury or hexachlorocyclohexane suffer from liver and kidney damage.

Future outlook

The scientific challenge of monitoring and assessing the risk of chemical exposure in the ocean depends on a strategy for the selection of priority substances and the integration of an analytical cost that is bearable given the geographical extent of the coastal and offshore zones involved. The choice of sites of interest must include their vulnerability, such as coastal and estuarine areas, polar zones and deep-sea areas. The third challenge concerns the development of analytical approaches to assess traces of emerging chemical contaminants in the water column, sediment and biota. Analytical quality is a *sine qua non* for long-term monitoring. The fourth challenge is to assess the biological effects of chemical contaminants and their transfer to the food chain. The identification of biomonitoring strategies in the case of chronic or accidental contamination requires knowledge of the species ecology and of the typology of the sites. Advances in monitoring methods in the past 30 years make it possible to combine substance ‘prioritizing processes, chemical traces of certain emerging contaminants and biological effects on natural habitats. This methodology will have to be flexible to be able to respond to the challenges of a growing chemical contamination composed of increasingly diversified emerging substances.

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13. Oil spills: recurring disasters

Jacek Tronczynski

The French name for oil spill 'marée noire' (literally 'black tide') was used for the first time by a journalist from the *Télégramme de Brest* to describe the damage caused when the tanker Torrey Canyon grounded in March 1967 off the southwestern tip of Cornwall (Fig. 1). Still in use, the term describes a vast oil spill in the marine environment, often with devastating ecological, economic and human consequences. Oil spills are commonly associated with accidental events, such as the shipwreck of a tanker or a large release from offshore or coastal petroleum installations. Large oil spills have also been caused by armed conflicts, such as the contamination of the coral reefs in the Red Sea, during the 1991 Gulf War.

What we've learned

The oil spill caused by the Torrey Canyon and the series of oil spills that followed off the coasts of North America clearly reveled the lack of technical preparedness for offshore and coastal oil pollution emergency response. The spills also underlined the lack of scientific knowledge and of international regulations and laws applicable to such complex events. Efforts to reinforce the prevention and control of oil pollution include the progressive introduction of dissuasive measures, bigger fines, vessel reporting services, legal responsibilities and the technical developments of floating dams, recovery systems, the improvement of chemical dispersants, the provision of pollution recovery vessels... New marine observation and monitoring systems (airborne, satellite, acoustic...) have emerged, and interdisciplinary scientific research projects aimed at a better understanding of the fate of oil and its ecological impacts, as well as the risks to human health, have been implemented. Today, complex risk assessment models enable more accurate identification of the most exposed areas, such as the western English Channel, due to shipping conditions, and the Arctic, due to climatic conditions and the expected development of oil and marine transport following ice melting.

Finally, environmental policies have been developed within the framework of international and regional treaties and agreements. Thus, after the first oil spills, the International Maritime Organization (IMO) promulgated the MARPOL International Convention for the Prevention of Pollution from Ships, in 1973. The Convention now covers oil pollution, pollution by other hazardous substances transported by sea, waste waters, litter, and atmospheric pollution by ships. At the European regional scale, the Bonn Agreement was drawn up in 1969 by the eight states bordering the North Sea, but was not activated until the accident on the Bravo - Ekofisk oil platform in 1977 and the sinking of the Amoco Cadiz in 1978. Following the shipwreck of the Erika in 1999 and of the Prestige in 2002 in the Bay of Biscay, the European community also created technical institutions. In 2002, the European Maritime Safety Agency (EMSA) was established to provide technical expertise (such as satellite based detection of marine pollution) and operational assistance, including making oil recovery vessels and other means

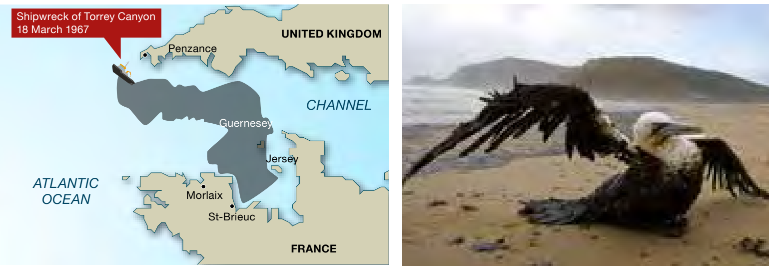

Fig. 1 – **Left: the Torrey Canyon spill (source Courrier International). Right: on a beach in Galicia, after the sinking of the Prestige. © P. HANNA / Reuters.** ■

of oil spill emergency response available to Member States. In France, the grounding of the Amoco Cadiz led to the creation of the Center of Documentation, Research and Experimentation on Accidental Water Pollution (CEDRE), in 1978.

The tightening of regulatory standards coupled with technological developments has strengthened prevention and control capacity and improved intervention protocols.

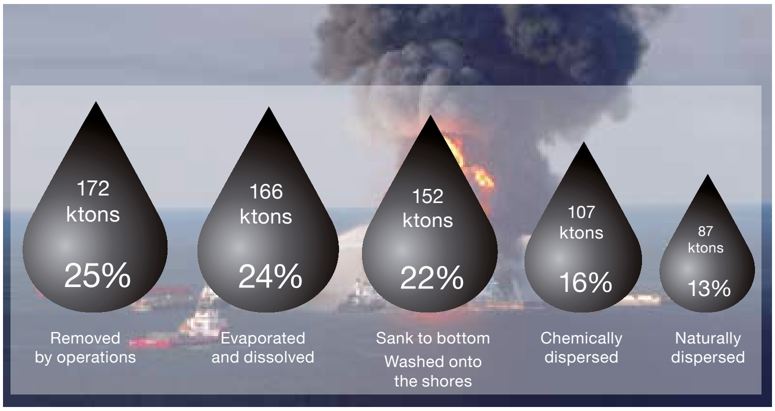

Fig. 2 – **What became of the oil?** Explosion of the Deepwater Horizon rig in the Gulf of Mexico April 2010. © Handout / US Coast Guard. ■

Assessments

To assess the ecological impacts caused by an oil spill, we need to understand the fate and behavior of the spilled oil. Remote observations and hydrodynamic and meteorological modeling make it possible to follow and forecast the drift and washing ashore of oil slicks. Scientists also assess the amount of oil discharged, the geographical footprint of the disaster and identify the most threatened areas. They study the type of oil, its persistence, its behavior and its distribution in marine compartments (water, sediments, atmosphere, biota) and on coasts (rocks, sand, pebbles, vegetation...).

During the explosion of the Deepwater Horizon oil rig in the Gulf of Mexico in 2010, nearly 680,000 tons of crude oil escaped in three months (Fig. 2). Seventy-five percent of the oil was dispersed in the environment, evaporated into the atmosphere, dissolved in the water, deposited on the sea bottom, washed up on the coast, dispersed chemically or naturally through bacterial action and sea dynamics. The cumulative spatial footprint extended between 120 and 176,000 km^2. Another example is the grounding of the tanker Exxon Valdez in 1989 in Alaska, which resulted in the spill of 42,000 tons of crude oil and contaminated 1,990 km of coastline. These pristine areas paid a large toll: the death of mammals and seabirds, and damage to macroalgae and benthic invertebrates. Twenty-five years of scientific observations now reveal the long-term consequences of this oil spill for the Arctic marine ecosystem. The prolonged exposure of fish embryos to polycyclic aromatic hydrocarbons has delayed growth and affected behavior, with consequences for the survival and the reproduction of adult fish. Prolonged exposure of populations to residual pollution of their functional habitats (nurseries, spawning grounds) has also had a series of indirect effects. A new ecosystem-based approach to ecotoxicology is therefore needed to assess the ecological impacts of these disasters. Studies that have provided evidence of long-term damage to marine populations in Prince William Sound enabled the US federal authorities and the State of Alaska to oblige Exxon to pay hundreds of millions of dollars in damages and several billion dollars on clean-up operations.

Large oil spills attract attention, but regular oil pollution surveys around the world between 2004 and 2013 indicate a median of 29 incidents every year and a median amount of cumulative releases of about 30,000 tons per year. Oil spills are indeed a real ecological, economic and human regional trauma, but they represent only a portion of the global chronic contamination of the oceans by petroleum hydrocarbons (19%), while the contribution due to routine operational discharges (deballasting, degassing...) accounts for more than 40% of anthropogenic inputs.

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14. Plastic debris in the sea

Alexandra Ter Halle and Maria Luiza Pedrotti

Since its commercial development in the 1950s, plastic has been a real success story. Its world production continues to expand exponentially. It reached 288 million tons in 2012, an increase of 620% compared to 1975. The success of plastic is due its remarkable qualities: easy to shape, low cost, imputrescibility, mechanical strength, shockproof... The ideal material for packaging, which is also its main sector of use (40 to 50%, according to Plastique Europe). Eighty percent of the waste at sea comes from the land and mainly from poorly collected and non-recycled household waste. In 2010, mismanagement of household or municipal waste is said to have generated 5 to 13 million tons of plastic in the oceans. More worryingly, by 2025, this number will be multiplied by 10: 50 to 130 million tons of plastic poured into the oceans every year. All the ecosystems of the planet are concerned, even the most remote places. Bays, estuaries, lakes, deserts, and abyssal plains are also contaminated with plastic. Rivers and water streams, although not yet sufficiently well studied, are the main means of transportation of plastics to the sea.

Plastic debris degrades very slowly and persists in the marine environment. Under the effect of circular oceanic currents, plastic waste accumulates in subtropical gyres. There are five such accumulation areas in the North and South Pacific, the North and South Atlantic and the Indian Ocean. The largest accumulation area in the North Pacific is almost six times the size of France, or 3.4 million square kilometers (Fig. 1). The concentration of plastics in the Mediterranean region is similar to that of oceanic gyres where these continents of waste are formed.

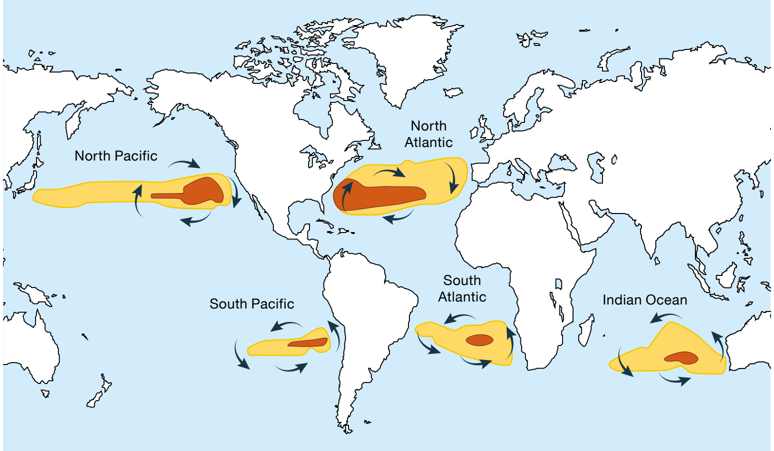

Fig. 1 – **The five waste accumulation areas in the world ocean.** The large accumulation area in the North Pacific is also known as the 'seventh continent'. Source: laboratoire des IMRCP. ■

Plastic fragmentation

To meet the requirements of its varied uses, plastic is designed to be rot-resistant and to last, but once in the environment, these properties become disadvantages. Depending on the nature of the plastic, its lifespan can range from a few years to several centuries. At sea, plastic breaks up due to wave abrasion and solar radiation (Fig. 2). The majority of debris in the oceans is produced by the fragmentation of macro-waste with the continuous release of fragments that are only of a few millimeters in size (microplastic). But plastics are also found at sea in the form of microparticles, derived from cosmetics, toothpaste and textile fibers released by our washing machines. A total of 5,000 billion plastic particles are estimated to float in our oceans. The abundance of microscopic particles in the natural environment is not yet well understood by the scientific community, but this aspect is even more worrying.

Impact on marine organisms

In the marine environment, a wide range of organisms, from plankton to large vertebrates, such as fish, turtles or whales, interact with plastic waste. Each year, more than 100,000 marine mammals and one million birds are estimated to die trapped in plastic bags or after ingesting floating waste they confuse with prey. Microplastics are more complex, invisible and difficult to treat. Due to their small size, they are loaded with toxins and can be ingested by all filtering organisms, including mussels and oysters, and thus easily enter the food chain. They are the same size as the plankton on which fish and whales feed. Many organisms are grafted on this floating waste: bacteria, algae and crustaceans. Transported by currents, plastics can displace exotic or harmful species thousands of miles, severely disrupting ecosystems.

Chemical pollution

Chemical pollution is also associated with plastic debris. The chemical compounds transported by plastics are mostly incorporated during manufacture (mainly additives). But plastics also have the ability to accumulate and concentrate pollutants in rivers or seawater during their long stays in the environment. Some bio-available chemicals are then transferred to the animal organisms that ingest them and bioaccumulative molecules can then concentrate along the food chain. Finally, some of the substances associated with plastic debris are toxic and can have chronic effects.

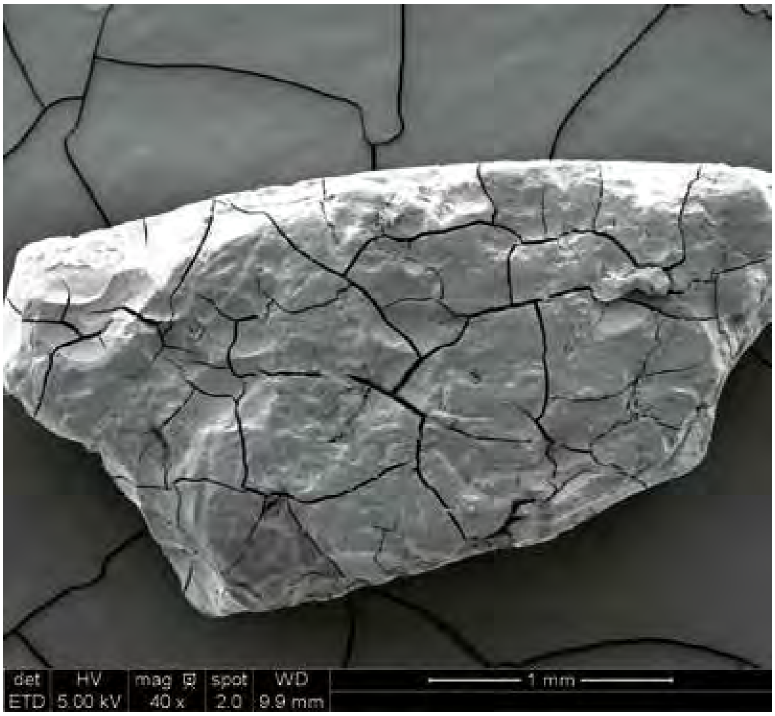

Fig. 2 – **Highly fractured micro shell (a few millimeters on size) that will break into smaller particles, invisible to the naked eye.** Image obtained by scanning electron microscopy. Source: IMRCP laboratories. ■

How to reduce the amount of plastic waste?

Plastics are now considered to be a threat to the marine environment. Scientists are trying to understand what happens to these particles in order to predict their impacts on the oceans and on humans. Nevertheless, as total ocean clearance is not possible, reduction of upstream pollution at the source must be achieved through integrated catchment management, water sanitation and improved waste management (collection and recycling). Controlling plastic pollution also involves promoting recycling and the circular economy. These measures must be simultaneously accompanied by a change in our consumption behavior, through education and citizen awareness, because the health of the sea and the oceans depends on each of us. The accumulation of waste in the sea is a global problem that requires comprehensive and coordinated solutions.

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15. Ocean noise pollution

Yann Stéphan, Florent Le Courtois and G. Bazile Kinda

The marine environment is an excellent guide to sound waves, which can propagate over hundreds of kilometers, whereas light penetrates only a few meters. Many marine species exploit this property of the ocean to communicate, locate or spot their prey. Underwater noise pollution caused by human activities can endanger the health of ecosystems, whose scales of adaptation are not always as rapid as the changes undergone by our societies.

Sound diversity

A wide range of natural sounds is emitted in the marine environment, for example, by geophysical phenomena. To this geophysical chorus must be added the biological chorus generated by living organisms. Whales sing at low frequencies and these sounds can spread over several hundred kilometers. Dolphins whistle and 'sound' their surroundings with specific signals called 'echolocation clicks'. Other species emit sounds of all kinds, such as grunts or snaps. Many listen to their environment to communicate, detect prey or flee predators. Living organisms can also produce incidental sounds by moving and feeding.

Through their offshore activities, humans add their contribution to natural submarine soundscapes. The use of underwater sound sources has become widespread for seismic prospecting, the detection of objects, estimating fish stocks, measuring ocean depth, submarine communication... The lower the frequencies and the greater the power of the sound source, the greater the propagation distances. Moreover, many human activities are also noisy by nature. For example, vessels and powered vehicles are sources of noise that emit continuously over time mainly at low frequencies. Works at sea, such as those related to the development and exploitation of renewable marine energies, also generate noise in the marine environment.

The study of sounds

Sounds are defined by their duration, their frequencies and their level, the latter being expressed in logarithmic scale, the decibel (dB). Two sources with the same level of sound do not produce twice as much perceived noise; conversely, the arrival of a source in a quiet place can considerably increase the perceived noise.

Underwater acoustics provide two essential tools for understanding the risks of noise pollution in the marine environment. The first is the observation of the sounds in the environment by submarine microphones, called hydrophones. These instruments measure the underwater soundscapes, their temporal dynamics, their volume, and their frequency content (Fig. 1). They make it possible to compare the anthropic and natural components of the soundscapes in the same space of representation. However, considering the extent of maritime spaces and the propagation distances of sound waves, hydrophone observations can only provide sparse one-off observations. This is why the

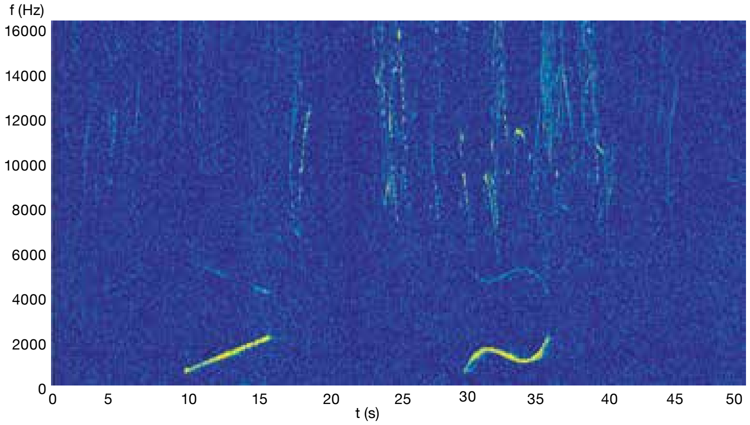

Fig. 1 – **Example of time-frequency representation of a recording.** The image makes it possible to estimate the signal frequency content as a function of time. The figure shows the whistles emitted by dolphins at high frequencies (above 8000 Hz) and signals emitted by the acoustic sources used in acoustic oceanography (under 2000 Hz). Source: Shom. ■

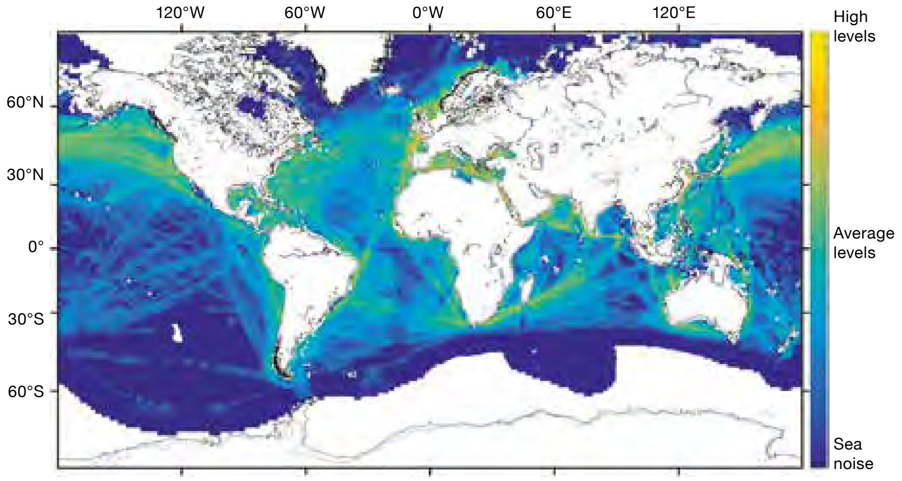

Fig. 2 – **Example of noise distribution of maritime traffic during the month of July 2012 for the one-third octave centered on 63 Hz.** The model is designed to estimate the sound levels produced by traffic and then propagate these levels at each point of the globe, in order to estimate the sound levels induced by traffic at different distances. Source: Shom and Lloyd's. ■

use of a second tool, spatial modeling, is essential. This enables noise levels to be estimated at the ocean basin scale (Fig. 2).

Too noisy an ocean?

Mass marine mammal strandings are a very strong ecological symbol, although the causes of such events are rarely precisely known. For beaked whales, more than 90% of mass strandings reported since the end of the 19th century took place after 1950; this period was marked by the development and intensification of the use of high-power sources, particularly in underwater warfare (sonars) and oil prospection (air guns). In particular, the linking of mass strandings with nearby naval exercises made it possible to formulate the first hypotheses of the traumatic impact of impulsive sources of human origin. The autopsy of animals stranded in the Canary Islands in September 2002, during an international military exercise, revealed lesions likely to be directly linked to decompression accidents, as well as acoustic trauma.

At the same time, the level of ambient noise is changing with the increase in maritime traffic. Several studies have compared the probability of stress in some whales caused by the noise of vessels. The risk of masking animal communications by boat noise is also an important issue. Changes in marine mammal vocalizations in terms of levels, durations or frequencies over several years of recordings were attributed to ambient anthropogenic noise.

A new environmental challenge

The effort of scientific research and the accumulation of knowledge have made it possible to publish increasingly urgent alerts on noise nuisance on marine life in general. These are beginning to be taken into account by environmental policies. In 2008, the European Community introduced underwater noise pollution into the Marine Policy Framework Directive. Implementation of nuisance risk management protocols, such as animal presence monitoring protocols, the soft start of sound emissions or acoustic damping have become common, encouraged and even regulated for certain uses. Other initiatives are also emerging, such as the incentive recently initiated by the Port of Vancouver in which quieter ships pay lower mooring costs.

The need to maintain anthropogenic noise at levels without risk to the health of marine ecosystems places human beings before the challenge of sound ecology: moving from the world of silence to that of harmony.

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16. Coastal urbanization and fragmentation of the environment

Christophe Lejeusne

> *'It is over five kilometers long. It does not end. Maybe six, or even seven kilometers. Mole A, Mole B, Mole C. It goes almost to the middle of the alphabet, the port of Marseille ...'*
>
> Albert Londres, 1927.

Rome, Athens, Alexandria and Marseilles are examples that remind us that many of the major European and Mediterranean urban centers are rooted in antiquity. But Europe really became urbanized only recently (after the industrial revolution) with, for example, 80% of the French population living in urban areas today. Although urbanization has expanded exponentially in recent decades, it has also to a considerable extent moved to the coast, resulting in an increased concentration of populations and human activities in the coastal zone and marked artificialization of coasts: 22 000 km^2 of European coasts are concreted or tarred, and in some regions of France, Italy or Spain, almost 45% of the first kilometer of the coastal strip is built up.

Disruption of marine ecosystems

The aim of the artificialization of the coast is often to create land from the sea or to protect the coastline in order to protect the densest coastal cities and their human activities. The Dutch polders, the Camargue saltworks, and the Venice lagoon are examples of protective structures. Walls, docks, dykes, moles, or breakwaters are used to counter storm surges and rising sea levels due to climate change. But the introduction of these physical barriers also changes marine currents and can disrupt the path of the larvae of many species (certain crustaceans and fish), which use currents as means of dissemination. These changes in connectivity between marine populations can either connect initially separated populations or separate previously connected populations. In the latter case, loss of genetic diversity and, ultimately, local extinction may result, especially if the recipient population is small or poorly diversified.

Another direct consequence of the artificialization of the coast is the direct destruction of shallow habitats that are often natural nurseries, especially for commercial species, which is the case of the Mediterranean white seabream (Diplodus sargus). Other indirect physical disturbances (water turbidity, hyper-sedimentation), particularly during the construction

Fig. 1 – **View of the entrances to the Old Port of Marseille and to the commercial port, showing artificial coastal defenses (dikes, riprap) and structures for human activities (platforms, pontoons). © C. LEJEUSNE. ■**

of structures, can further weaken and reduce coral and underwater meadows of posidonia or eelgrass, a multitude of other species that use them as shelter, pantry, breeding area and nursery. To this we should add various sources of pollution during the exploitation of artificial structures. Noise and artificial light at night caused by roads and harbors can disorient seabirds and fish larvae, hindering the recruitment of new generations. Similarly, chemical pollution (including hydrocarbons, endocrine disrupters, heavy metals) from the city or from human activities (industries, ports, wastewater treatment plants) can cause different types of physiological stress that affect the health of organisms and of coastal ecosystems. A notorious example is the masculinization of female murex (a common gastropod) in the presence of very low doses of TBT, now banned, originating from anti-fouling paints used on boats (cf. VI.12).

Fragmentation of habitats

Like the construction of a highway in the middle of a forest that destroys a part of it and affects the connectivity between the remaining parts, artificialization and coastal urbanization causes the fragmentation, thus threatening connectivity between marine populations and ultimately jeopardizing their survival. But, while destroying natural habitats, artificial infrastructures also provide new hard substrates that are very rapidly colonized. In areas where no hard habitat was naturally present, species typical of rocky substrates settled on the newly submerged structures, like the breakwaters constructed on Belgian's sandy coasts. Artificial structures are sometimes even used for the restoration and rehabilitation of the environment, the case of Prado Reef program in Marseille, in which 27,300m^3 of artificial reefs were submerged to revitalize traditional fishing. In most cases, however, the structures are not immersed for the purpose of restoration and a number of scientific studies revealed the originality of species assemblages occupying these new habitats. Thus, artificial habitats are not substitutes for neighboring natural habitats, and researchers have found, in particular, a higher concentration of invasive alien species, which together with climate change and habitat destruction are one of the main threats to biodiversity and as such, are a European Union environmental priority. In some cases, the multiplication of artificial structures appears to facilitate the dissemination of species by creating corridors and environmental conditions that favor their spread.

Artificial habitats are now one of the major challenges for the conservation of biodiversity and its associated services. Nevertheless, research on marine ecology in artificial environments is still relatively undeveloped, despite the considerable extent of urbanization along our coasts today. The situation calls for its rapid development.

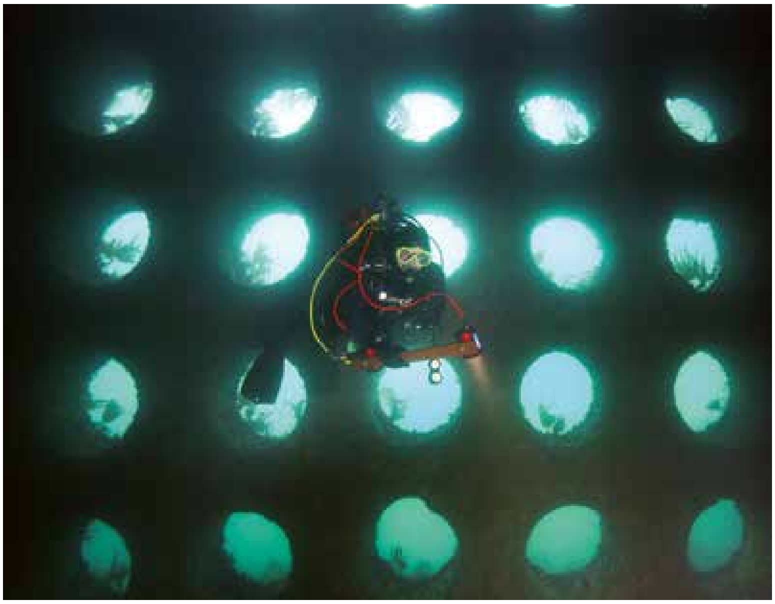

Fig. 2 – **View from inside the ferry dock in Bloscon port (Roscoff), showing the portholes in the structure built to break the sea swell, and the different organisms that have colonized them.** © W. THOMAS / Roscoff Biological Station. ■

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- PART SEVEN -

The governance of the ocean

Previous page:

Gold Coast in Queensland, Australia. © J. TASTULA. ■

1. Oceans under control

Philippe Cury, Sophie Arnaud-Haond and Françoise Gaill

In 1609, the Dutchman Hugo de Groot, known as Grotius, defended the freedom to navigate and trade throughout the seas in his work *Mare Liberum* (The Freedom of the Seas). The oceans were an open space, where humankind could trade and do business freely. In 1635, the Englishman John Selden published a riposte to Dutch dominance, the Mare Clausum (Of the Dominion, or, Ownership of the Sea), which questioned the need for ownership of the seas. A competition emerged for the incremental conquest of the oceans, just as had been the case on land, at the cost of conflict and wars. Given their highly strategic nature, the oceans and seas are without a doubt still the subject of fierce debate and conflicts of interest today. The nature of the debate has hardly changed in several centuries, but with the stakes now global, the distribution maps have been redrawn, reviving ambitions and with them, the issue of access rights.

What kind of governance is needed for marine resources that are shared between nations but are migrating in response to climate change? What type of access should be provided for humans who migrate on a global scale, with constantly evolving technologies, and who are diversifying the use of marine spaces and the exploitation of marine resources, with new types of geopolitical and biological implications? Will new access rights or strangleholds emerge with the restriction on the freedoms of the high seas and the congested use of seas that lap at often overpopulated coasts? With these challenges, new contexts are emerging, with an ever-greater number of increasingly more global geopolitical, economic, diplomatic and institutional environments.

The marine world now appears to be approaching the limits of its existence and is being rapidly appropriated, with the irreversible nature (in legal, ecological and other terms) of this appropriation highlighting the urgent need for careful consideration of the spatial planning and ownership of the seas.

This chapter brings together a series of contributions which outline the key points and the open questions for achieving a satisfactory outcome to the discussions that are now needed for the development of a coherent global biological and legal strategy for ocean governance.

What does international law, the very basis of the concept of ocean governance, which is being reinvented along with the emergent issues, have to say about the ecosystem approach to fishing, new genetic resources, climate change and the new challenges in the Arctic and Antarctic Oceans, the spatial management of the oceans, scientific overviews or the new role of international negotiations? These myriad questions require an understanding of current developments in governance, the development of practical proposals or consideration of new areas for research.

Saint Gilles coral reef. The reefs of Réunion Island are under significant threat from motor boats, fishermen, divers and increased levels of pollution. © IRD / A. BORGEL. ■

This review of the observations, international initiatives and global pressures associated with a new form of governance for the oceans is rapidly taking permanent shape. There is an obligation for decisions taken today to gather the best available expertise for collective decisions on the future of the oceans under the ever-more pervasive influence of the human community.

As an outcome from the joint action of scientists, civil society and certain countries, an analytical report on the ocean and the cryosphere in the context of climate change will shortly be available from the intergovernmental panel on Climate Change (IPCC). In the meantime, we look forward to reading synthetic articles in this chapter on which we can base our reflections on global ocean governance in the years to come.

2. Global ocean governance: a fragmented framework

Julien Rochette

'Marine species of use to man will become extinct unless their exploitation is subject to international regulation.' These are the words of Léon-José Suarez, in a 1927 report to the League of Nations. They explain why the international community worked gradually, over the 20th century, to develop measures for the conservation and sustainable management not of 'useful resources', but of marine biodiversity more widely.

The three pillars of global ocean governance

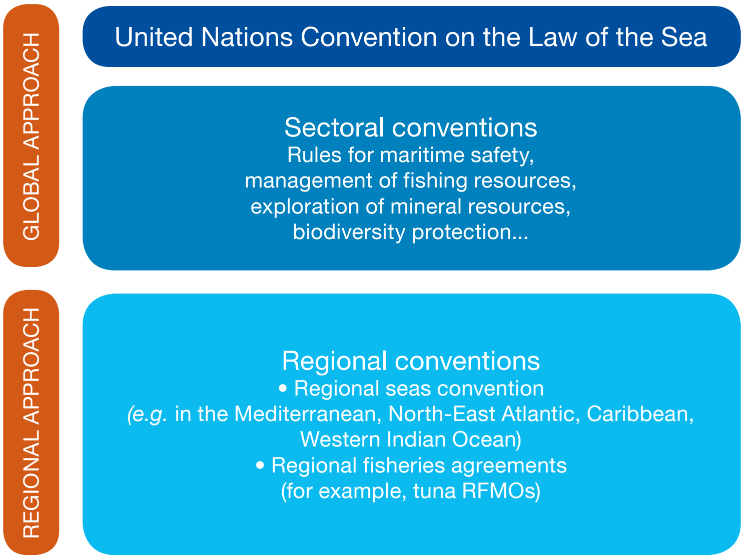
Negotiated from 1973 and adopted in 1982 in Montego Bay, the United Nations Convention on the Law of the Sea (UNCLOS) is what many call a 'Constitution for the Ocean'. It contains general requirements aiming to guarantee both the peaceful use of the seas and oceans, and the protection and preservation of the marine environment. Accordingly, beyond the rules governing maritime delimitations, UNCLOS requires States to prevent, reduce and manage marine environment pollution from different sources. These include land-based activities, oil and gas exploitation, shipping and the exploitation of mineral resources.

However, to be effective, these general requirements must be implemented through 'sectoral', conventions. These conventions are global legal instruments (open to the whole international community). They are designed to apply the principles of UNCLOS in various domains, such as fisheries resource management, combating pollution, protecting marine species and habitats...

Finally, as stated by the Brazilian delegate Gilberto Amado at the second United Nations Conference on the Law of the Sea, no two seas are alike ; this means that it is not and has never been easy to solve problems using a single universal formula. Indeed, how could a single international convention or a single programme of actions simultaneously combat coral bleaching in the Philippines, regulate oil exploitation in the Arctic, protect monk seals in the Mediterranean and manage the problem of macrowaste on the Hawaiian coasts? Therefore, after the Second World War, the Food and Agriculture Organization of the United Nations (FAO) instigated the development of the Regional Fisheries Management Organizations (RFMOs), which are in charge of managing resources in identified marine regions. From the mid-1970s, this time driven by the United Nations Environment Programme (UNEP), regional sea programmes were created to preserve the marine environment, in the Mediterranean, the North-East Atlantic, the Caribbean and East Asia, for example (Fig.).

A fragmented governance framework

This three-pillar system, put together progressively over recent decades, has generated a 'fragmented governance of the ocean'. This description refers to the hundreds of agreements, action plans, guidelines, codes of conduct and other instruments adopted to meet the challenges of managing the ocean sustainably. The list of intergovernmental organizations with a mandate on the marine environment further exacerbates this apparent fragmentation. For example, within the International Maritime organization (IMO), the States adopt rules designed to combat and remedy pollution from shipping. Meanwhile, the FAO is responsible for regulations on fishing techniques, catch volumes and the protection of certain species or habitats. The United Nations Environment Programme, the International Seabed Authority,



The architecture of ocean governance. Source: IDDRI / J. ROCHETTE. ■

the UNESCO Intergovernmental Oceanographic Commission and even the World Trade Organization also have a mandate on the marine environment. On top of all this, countless intergovernmental organizations have been created to protect certain marine regions.

Rationalising the system, whilst accepting its complexity

There is a clear need to rationalize ocean governance. In particular, efforts must be made to avoid overlapping responsibilities and strengthen the connections between the different international organizations. This is particularly relevant on the regional scale, where there are often fisheries organizations, regional seas programmes and economic organizations which all have responsibility for the marine environment. These organizations need to enhance their collaboration, in order to manage the marine environment on an ecosystem basis, rather than a purely sectoral one. The Mediterranean offers a perfect example of this need for coordination, with the coexistence of the European Union, the Mediterranean Action Plan, the Union for the Mediterranean and many other bodies. It is also essential to fill certain legal gaps, especially for areas beyond national jurisdiction. In this regard, the regime born out of UNCLOS is no longer sufficient.

Nevertheless, we must recognize that this frequently criticized fragmentation is inherent to the ocean governance system and its history. Each organization has its own purpose and it seems unrealistic to believe that the system can be unified. There is of course room for manoeuvre, to make the framework more coherent and effective. However, the governance framework is complex, because ocean management is complex. We therefore also need to work with this and make the most of the opportunities offered by existing conventions and organizations. In this respect, the United Nations Conference of June 2017 on implementation challenges on the Sustainable Development Goal on Oceans is an excellent opportunity to establish what needs to be done and coordinate current initiatives.

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3. Governance of the ocean: where science meets politics

Camille Mazé et Olivier Ragueneau

Since the 1960s, the ocean, from the coast to the high seas, has become the focus of a growing legal framework and increasing politicization, as demonstrated in its inclusion on national, regional, community and inter- and infranational agendas. This is true for coastal regions, in exclusive economic zones (EEZ), in the limits of national and offshore sovereignty and in international waters, shifting the notion of 'governance of the seas and oceans' from the closed, regulated vision of Selden's Mare clausum to the freer, more open view taken by Grotius in Mare liberum. From the legal practitioner's point of view, 'governance' refers to the standards and structures that comprise the mechanisms put forward by international and regional organizations (the UN, the European Union and regional conventions on the sea) and implemented by national governments to regulate the use of maritime spaces and ensure their sustainability. This context prompts an examination of the various forms of governmentality of the ocean.

Integrated coastal zone management and marine spatial planning are illustrations of this, as processes by which the public authorities divide up activities in coastal regions, in the maritime space and in the marine environment, with the aim of achieving sustainable development objectives of an ecological and economic nature. In contrast, 'international ocean governance' exists within the global legal structure of the United Nations Convention on the Law of the Sea, which established a set of territorial, institutional and regulatory frameworks (cf. VII.2), and is illustrated in the creation of targets, such as Sustainable Development Goal 14 (SDG14) to conserve and sustainably use the oceans, seas and marine resources for sustainable development. The Biodiversity Beyond National Jurisdiction (BBNJ) process, which aims to protect marine biodiversity beyond national jurisdictions, adds further legal weight.

Creating governance

The definition and establishment of 'governance' is not a straightforward matter and the real challenge for political social science is to unpick this process, with its strong sociological and anthropological focus on the stakeholders, institutions and groups that produce and implement the standards and devise the institutions and make them work. It is important that 'governance of the seas and oceans' should be an area of fundamental research, to elucidate its creation at the intersection of a number of social spheres and stakeholder categories, encompassing all levels of collective action and including differing interests and knowledge for hybridization.

In the contemporary geopolitical context and in the face of global change, coastal and marine areas are caught between a number of national, social and occupational groups, entangled in a tense web of conflicting representations which need to be reconciled, between commercial exploitation and conserva-

Map extract from a book by the German geopolitician Karl Haushofer (1869-1946), published in 1934, which criticizes maritime imperialism. Source: K. HAUSHOFER – *Weltpolitik von Heute*, 1934. ■

tion or preservation of the environment and resources, a free zone and common asset belonging to the whole human community, versus territorialization or even privatization. Usage, borders, movement, access to sites and resources and their use or commercialization (or otherwise), must be more clearly defined, orchestrated, administered and controlled. Given, though, that maritime stakeholders and states themselves are both subject to and the beneficiaries of these governmental policies, the task is particularly complex. This makes establishing multilevel, multisector or indeed integrated governance one of the most significant endeavours of our times. It provides the ideal vantage point for understanding the contemporary transformations in policy, which must be investigated with due consideration of effects of scale, rationale and stakeholder networks. More broadly, it enables us to take action to redefine how relationships between humans and nature are regulated, where the role of non-human entities, both in science and society is the subject of debate.

Working at the interfaces

The interface between science and society forms a particularly effective gateway to the study of 'governance', a concept which implicitly assigns society the central role in contemporary forms of government of the human relationship with nature. It refers to the reshaping of the ways in which public action is managed, taking it in a more participative and democratic direction, beyond the conventional branches of government. It might also embody criticism of the dominance of private interests, help to alleviate government shortcomings and link the different forms of regulation with the integration of distinct groups and interests. The relationship between science and society as a boundary zone in the decision-making and public action process is key, reflecting political transformations as it changes and develops. From a confined relationship at the intersection between science and politics in historical forms of government, there is a shift towards a more open approach, broadening out the interface to a relationship between society and politics that encompasses science and other social spheres. Scientists and experts, with their so-called 'legitimate' knowledge, remain fully involved, from knowledge creation through to application, but they are increasingly expected to integrate the outputs of their research with other kinds of home-grown, commonplace or layperson's knowledge.

Opposing interests, conflicting group representation strategies and resistance to conventional forms of government, despite activity such as desectoralization and integration, are still making it difficult to establish effective national and international 'ocean governance'.

An issue of power relations

The governance of the seas and oceans exists at the point where a number of social spheres intersect: science and expertise, economy and industry, and defence and geostrategy. These various aspects are consolidated in the crucial issue of access to resources, how they are shared and managing them sustainably. This is the key to the definition of 'good governance' of the ocean, with all the normative connotations (in the imperative sense) of this term. The need to evaluate effectiveness implies the definition of criteria and indicators, and the activity of developing these will itself require investigation. It needs to be recognized that insufficient heed is given to scientists' recommendations and that major issues remain regarding public action on the sustainability of the oceans. From representation in negotiating arenas, to collective involvement in alliances or organized interest groups, there is a need for analysis of cross-sectoral power relationships to resolve the bottlenecks that are hampering the implementation of sustainable management of the oceans and seas.

The social-ecological system approach, as it is being developed in the field of sustainability sciences, where more interdisciplinary, participative, solution-oriented fundamental science is promoted as a useful source of inspiration, provides a suitable scientific framework for unpicking these relationships and clarifying the issues. The in-depth examination of the power relations in the governance of marine and coastal socio-ecosystems, combining political social sciences and natural sciences, needs to be reinforced to contribute to the transformative approach of sustainability sciences.

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4. The World Ocean Assessment

Françoise Gaill

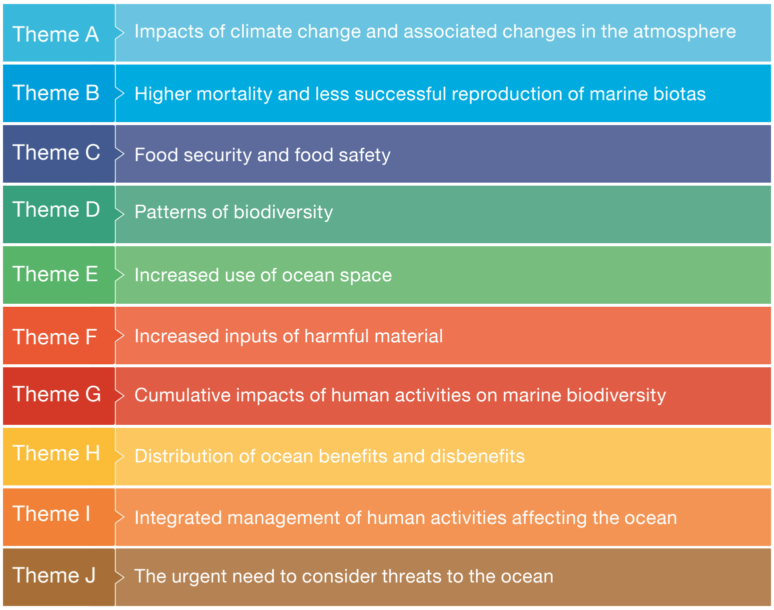
In 2002, at the World Summit on Sustainable Development, a process to review the state of the marine environment, including socio-economic aspects, and periodic monitoring, was recommended. The Secretary-General of the United Nations decided to establish such a process in order to have a regularly updated overview of the state of the ocean. This 'state' had to concern as much the dynamics of the ocean as the way in which humans make use of them. This type of evaluation should enable anyone, whether individuals or institutions, involved in the wider management of the marine environment, to make informed decisions about the actions to be taken in the context of the global ocean.

Methodology of action

Given the scale and complexity of the approach, a methodology was needed to achieve these objectives. Two international symposia devoted to defining the methodology took stock of more than 2,600 reports falling within the scope of the objective concerned, for instance the mapping of a particular species in a specific region or the synthesis of a specific type of pollution generated by a metallic element at the global level. These reports were identified, analyzed and synthesized (in a document entitled 'Assessment of assessment'). The UN General Assembly then established a working group called the Ad Hoc Working Group of the Whole, to consider the recommendations of the work, and to make proposals. This group was headed by the Division for Maritime Affairs and the Law of the Sea. The framework and implementation modalities proposed by the group were approved in 2009 by the General Assembly. Two years later, in 2011, it set up an office to monitor the work of an expert group (Group of Experts of the Regular Process), composed of 25 people charged with producing a summary entitled 'World Integrated Assessment Marine Environment' (World Ocean Assessment, WOA, Fig. 1). This synthesis had to be carried out *via* a process called '*The Regular Process for Global Reporting and Assessment of the State of the Marine Environment, Including Socioeconomic Aspects*'. The plan for a global report was accepted in 2012.

The drafting of the report's various parts was entrusted to a second pool of experts, covering all the scientific fields required for this encyclopedic work. These new experts, proposed by the states, were selected by the initial group of experts and then approved by a conventional UN mechanism under the responsibility of the regional officials. Of the 800 names proposed for the chapters, 250 were selected. A parallel group of reviewers was also set up to review and criticize the articles written by the 250 experts. Lorna Inniss (Barbados) and Alan Simcock (United Kingdom) were nominated as the two coordinators of the expert group of the '*The Regular Process for Global Reporting and Assessment of the State of the Marine Environment, Including Socioeconomic Aspects*'.

Fig. 1 – Coverage of the World Ocean Assessment I, to be published by Cambridge University Press. ■



Theme A	Impacts of climate change and associated changes in the atmosphere
Theme B	Higher mortality and less successful reproduction of marine biotas
Theme C	Food security and food safety
Theme D	Patterns of biodiversity
Theme E	Increased use of ocean space
Theme F	Increased inputs of harmful material
Theme G	Cumulative impacts of human activities on marine biodiversity
Theme H	Distribution of ocean benefits and disbenefits
Theme I	Integrated management of human activities affecting the ocean
Theme J	The urgent need to consider threats to the ocean

Fig. 2 – **The 10 themes identified in World Ocean Assessment I.** Adapted from the UNEP-WOA overview (www.unep.org). ■

First report on the global state of the oceans

This report is impressive because of the breadth of the scientific fields covered. More than answering current questions, it presents facts and makes a diagnosis on a given environment. It is the zero point of knowledge of the ocean, from which it is now necessary to start to know how this ocean will evolve tomorrow. It places this knowledge in the sphere of present and future human activity and sketches answers to several fundamental questions: What is the global state of the seas and oceans at the beginning of this century? Are marine ecosystems healthy and, if not, who is at risk? What services do the oceans provide to us and how are these benefits distributed geographically? Finally, what are the threats to these environments and how can we measure the state of tomorrow's seas and oceans?

The 55 chapters of the final document (WOA) cover 10 topics presented in a summary to governments and all decision makers (Fig. 2). They provide a holistic view of ocean-related issues, which can be reviewed periodically to illustrate the critical importance of knowledge-based documents in policy modalities. This report is remarkable for the unusual importance attached to marine biodiversity, ecosystem services and human activities in the marine domain. It was presented to the General Assembly on September 8, 2015 and adopted in December of the same year, which was too late to be available at the time of COP 21 in Paris. Due to the temporality of UN actions and the intergovernmental working group response time to the questions posed by the States, it took almost 15 years between the beginning of the initial discussions and the formal adoption of the report.

The content of the WOA was inconspicuously criticized for its heaviness, its classicism, for not taking into account the most recent data and for its lack of ambition. In fact, it was more a knowledge atlas than a collection of statements and thesis demonstrations. On the other hand, the little publicity it received is also to be highlighted, since this whole process was to benefit from the support of UN structures involved in the ocean (IOC-Unesco, FAO, UNEP, AEIA and IMO).

What now?

The second World Ocean Report is currently being implemented. It will cover over the period 2017-2020 and must be carried out in the context of three major global challenges: the 2030 Sustainable Development Agenda, the Preparatory Conference for the Development of an International Binding Instrument for Conservation and Sustainable Management of marine biodiversity beyond areas under national jurisdiction (BBNJ process) and the United Nations Framework Convention on Climate Change. It is in the light of these three aspects that the second 'WOA' will have to provide answers to the questions asked: aspects that are missing and to be dealt with, those that are outdated or to be reviewed, new questions to consider in order to be able to act at planetary scale and protect the ocean...

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5 The ocean in IPCC reports

Valérie Masson-Delmotte and Jean-Pierre Gattuso

Set up in 1988 under the guidance of the United Nations Environment Programme (UNEP) and the World Meteorological Organisation (WMO), the Intergovernmental Panel on Climate Change (IPCC) produces reports based on scientific, technical and socio-economic information to assess the physical evidence of the risks associated with human activity on the climate, the potential impacts and the options for adaptation and mitigation. The IPCC's reports deliver a critical evaluation of the state of knowledge and must remain relevant if they are to facilitate political choices, although they are not prescriptive. The IPCC does not conduct research but stimulates knowledge production.

The IPCC has three working groups (I - Physical scientific basis, II - Impacts, adaptation, and vulnerability, and III - Mitigation) plus a task force responsible for defining methodologies for greenhouse gas inventories. It issues very comprehensive reports on the state of knowledge, which serve as a foundation shared by different governments and feeding into international negotiations on climate conducted as part of the United Nations Framework Convention on Climate Change (UNFCCC).

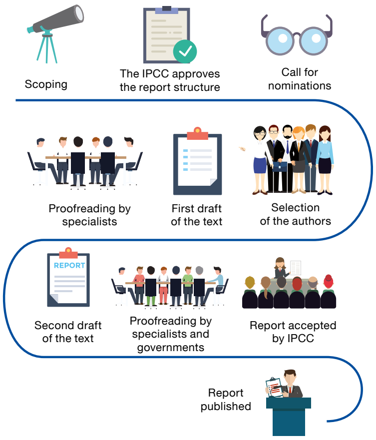

Fig. 1 – **Methodology for preparing IPCC reports.** ■

The Ocean in the fifth IPCC report

Of all the IPCC's reports, its fifth publication contains the most extensive coverage of the ocean (in reports from its working groups I and II), with three dedicated chapters compared to just one chapter in the fourth report. The key word 'ocean' occurs 2.5 times more in the fifth summary report than in the fourth.

The fifth report concludes that the warming of the ocean surface (especially in the first 75 metres' depth) and the deep sea is attributable to the storage of 90% of the additional energy accumulated by climate systems between 1971 and 2010. It extends its analysis to changes in surface salinity, pointing to an increase in hydrological contrasts since 1950. The ocean has also absorbed approximately 30% of anthropogenic CO_2 emissions, leading to an increase in seawater acidity (26% rise in hydrogen ion concentrations, cf. II.9). There has also been strong progress with attribution of the changes observed and the fifth report concludes that human influence has very likely contributed to the melting of the Arctic ice cap since 1979, to the warming of the ocean surface (up to 700 m depth) and the rise in sea levels since 1970. Some of the impacts of acidification on sea life are now attributed to human influence.

Based on forecasts made using climate models, the fifth IPCC report confirms that the oceans will continue to get warmer, become more acidic and lose oxygen. The expanse of the Arctic ice cap will fall and the average sea level will rise further. The coral reefs and polar ecosystems are the marine organisms and ecosystems under the greatest threat from these environmental changes (cf. VI.3). Coastal systems and low-lying coastlines will be considerably affected by rising sea levels which, even if the average temperature of the Earth stabilizes, will continue for several centuries. By 2050, the redistribution of marine species and biodiversity loss in sensitive regions will affect the sustainability of the fishing industry and other ecosystem services, particularly in tropical regions. Ocean acidification will continue for centuries if CO_2 emissions do not cease. This scientific finding weighed on the definition of the goals set out in the Paris climate agreement and its specific reference to marine ecosystems.

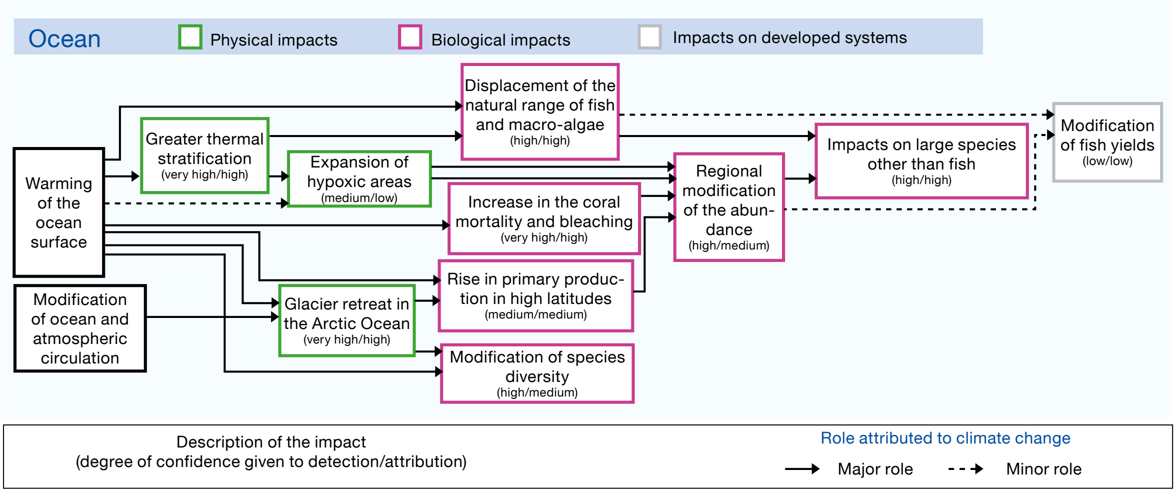

Fig. 2 – **Diagram from the IPCC fifth summary report illustrating the risks for oceans and possibilities for adaptive actions.** New elements indicate that the recent modifications to the climate have had interconnected impacts, with a domino effect, on the oceanic system. ■

Challenges for the sixth cycle of assessment

For the sixth IPCC assessment cycle, three special reports will be prepared, two of which will concern the ocean. The first (September 2018) will cover the impacts of warming of 1.5°C. It will include the ocean-related aspects required to assess additional impacts (and impacts avoided by preventing greater warming), and to assess greenhouse gas trajectories compatible with climate stabilization (accounting for thermal inertia of the oceans and carbon cycle feedback), in the context of a strengthening of the response to threats from climate change, of sustainable development and efforts to eradicate poverty. The second report (September 2019) will cover climate change, the oceans and the cyrosphere. It will look at the polar regions, rising sea levels and the implications for coastal zones and communities; changes to the oceans, marine ecosystems (including 'blue carbon') and the implications for communities that depend on them; the risks related to extreme and sudden events, and the management of these risks, with special focus on low-lying areas (islands and coasts).

This report will not cover marine renewable energies, which will be assessed alongside other renewable energies in the sixth report.

The full report from each working group will be prepared for 2021 and the summary report for 2022. We expect significant advances to be made with knowledge of the oceans thanks to new observations, better understanding of the processes, modelling tools working to a finer spatial scale, and the inclusion of the oceans in decadal predictability. The assessment of the risks that come with rising sea levels at regional level and in the long term, will likely be refined, along with the evaluation of the various options available to deal with this. We also expect greater coverage of regional oceanic aspects, upswelling phenomena, which are of great importance to marine ecosystems, and options for adaptation and mitigation solutions from an 'ocean' viewpoint: marine renewable energies, solutions based on ecosystems, protected marine areas in the context of climate change, coastal development scenarios, potential and risks from geoengineering initiatives, governance, and so on.

This very dense programme of work is an opportunity to keep decision-makers and the public regularly informed on the progress made in knowledge between now and 2022. We also hope that the extensive, rigorous scientific work carried out by the researchers to write these reports will be disseminated more widely, in the form of summaries aimed at young people for use in education, teaching and training.

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6. Governance challenges in the Arctic

Mathilde Jacquot and Emmanuelle Quillérou

The Arctic is a place of transit and of settlement. Economic activity there is intense, marked by wide disparities in an environment renowned for being 'difficult' or even 'hostile'. Shrinking of the ice cap due to climate change is opening up access to Arctic shipping routes, living (fish) and non-living resources (hydrocarbons, minerals), as well as places of tourist interest, thereby offering new opportunities for economic development (Fig. 1). Competition is becoming more acute for access to resources from the seabed up to the surface. All the conditions are in place for a 'cold rush' to arise, along with its adverse economic, social, environmental, and diplomatic consequences.

The Arctic faces two major governance challenges. The first is reconciling the interests of very diverse stakeholders for harmonious economic development. The second is expanding institutional capacity fast enough to establish the necessary environmental, social, legal, and diplomatic safeguards.

Expansion of human activities in the Arctic is inevitable. Effective governance is complex since the Arctic has many definitions. The 'race to the cold' has already started, with strategies switching between building pressure and cooperation. Maritime boundaries still need to be formally agreed upon by all parties involved (Fig. 2). The Commission on the Limits of the Continental Shelf needs to rule on a few applications for extension of continental shelves rich in hydrocarbons and minerals. There is no consensus on the legal status of the Northern Sea Route and Northwest Passage. Iceland has taken advantage of the lack of a regional fisheries management organisation in the Arctic to unilaterally increase its mackerel quotas. Choices for development, coordination and cooperation will have a major impact over the Arctic in the coming years.

Fig. 1 – Climate change is opening the way for the development of the Arctic, but the environmental and social impact is not neutral. © tpsdave / Pixabay. ■

Arctic fora for cooperation

The Arctic is a place where cooperation and dialogue are cultivated. The main intergovernmental forum is the Arctic Council. This forum was established in 1996 to promote cooperation, coordination and interaction among Arctic states. Its members – Canada, Denmark, the United States, Finland, Iceland, Norway, Sweden and Russia – can discuss common management issues, often related to sustainable development and environmental protection. Indigenous and local communities have specific representation within the Council, and their views are taken into account. Permanent observers – currently 12 non-Arctic states – take part in the discussions. In addition to fostering dialogue, the Arctic Council has promoted the production of scientific assessments in partnership with the International Arctic Science Committee (IASC).

At the instigation of the Arctic Council, the Arctic Economic Council, consisting of 36 business representatives, was established in 2014. Its objectives are to foster business development in the Arctic, deepen circumpolar cooperation and provide a business perspective to Arctic Council projects.

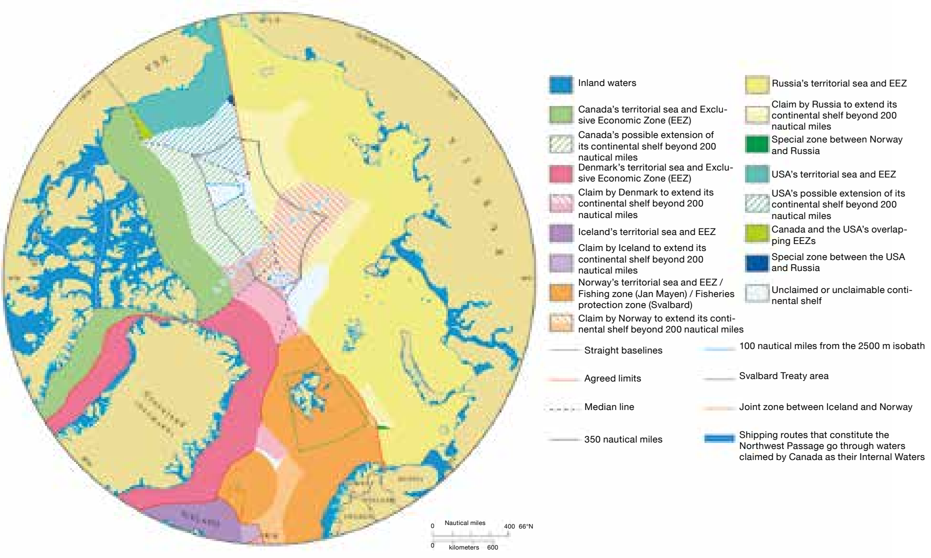

Fig. 2 – **Jurisdictional conflicts around the Arctic Ocean.** © IBRU, Durham University, UK. ■

Legal framework

A few but important binding international agreements apply to the Arctic. The United Nations Convention on the Law of the Sea (UNCLOS) provides the main framework. UNCLOS allows for regulation of marine areas by providing clear delimitation of maritime boundaries and a clear framework for access to resources, maritime navigation, protection of the marine environment, and scientific research. Other major international conventions apply in the Arctic, particularly for environmental protection and the fight against climate change. The 'Polar Code', the international code for ships operating in polar areas, adopted under the International Maritime Organization came into force on January 1st, 2017. It is a binding legal instrument for navigation in polar waters, with strong regional implications for the Arctic. Its normative prescriptions supplement the International Convention for the Safety of Life at Sea (SOLAS), and International Convention for the Prevention of Pollution from Ships (MARPOL).

At the regional level, the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) sets a framework for international cooperation to protect the marine environment which extends to a portion of the Arctic Ocean. Under the Arctic Council, two binding agreements have been signed between Arctic states: the first on the organisation of search and rescue after an accident (2011) and the second on the preparedness for and fight against marine pollution by hydrocarbons in the Arctic (2013). As a way around the lack of a specific regional fisheries management organisation, the five Arctic states adopted in 2015 a declaration concerning the prevention of unregulated high seas fishing in the central Arctic Ocean.

Scientific research

Several international organisations carry out scientific research, monitoring, scientific initiatives and projects in the Arctic: International Arctic Science Committee, Polar Council, French Arctic Initiative… Non-Arctic states are active providers of scientific expertise and research funding. These scientific collaborations can support the establishment of common and recognised international scientific foundations, thereby helping to build trust and enhance cooperation in the Arctic. At a time when the European Union and other non-Arctic states are developing their own Arctic strategies, widening diplomatic and scientific cooperation beyond Arctic states could help foster more harmonious development of the region.

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7. Which governance for Antarctica?

Yves Frenot

During the international geophysical year of 1957-58, more than 60 countries collaborated to conduct research in Antarctica, a region that was particularly poorly known at the time. The success of this event during the Cold War led to an extension of the political experience. Twelve states, including France, decided to create a new governance tool, the only one of its kind: the Antarctic Treaty, which entered into force on June 23, 1961.

The Antarctic Treaty

This Treaty is based on the principle of freezing land claims (Fig. 1), the prohibition of military activities and the desire to reserve the continent for scientific research in the framework of cooperation between countries. It applies to the entire area south of 60°S latitude, including the continent, the adjacent ice shelves, the neighboring islands and the ocean itself.

The original signatory states, and subsequently the other states which have acceded and actively undertake scientific research, have consultative (voting) status. They meet annually for the purpose of exchanging information, consulting on matters of common interest and advising their governments to serve the principles and objectives of the Treaty. In 2017, 53 States are parties to the Treaty, 29 of which have consultative status (hereafter called the Consultative Parties, CPs).

Since its inception, the Treaty has progressively enriched other instruments: the Convention for the Protection of Antarctic Seals (CCAS, London, 1972); The Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR, Canberra, 1980); The Protocol to the Antarctic Treaty on Environmental Protection, or the Madrid Protocol (1991), which aims to ensure the protection of the Antarctic environment by designating the continent as a 'natural reserve devoted to peace and to Science'; and the Convention for the Protection of Albatrosses and Petrels (ACAP, Cape Town, 2001).

From the outset, the Madrid Protocol has had four annexes, dealing respectively with impact assessments prior to any activity in the Treaty area, protection of fauna and flora, waste management and the prevention of marine pollution. In 2002, a fifth annex on the management of Specially Protected Areas entered into force. Finally, in 2005, a sixth annex was adopted, specifying the liability regime for environmental damage. At the time of writing, 2017, the sixth annex had not yet come into force.

Resource protection

Article 7 of the Madrid Protocol is undoubtedly the best known to the general public, since it establishes that '*any activity relating to mineral resources, other than scientific research, is prohibited*'. It is also the most misunderstood by the media, which generally mistakenly asserts that this moratorium will end 50 years after the entry into force of the Protocol in 2048. In fact, Article 25 of the Protocol provides that it can be amended at any time with the unanimous agreement of the CPs (currently 29 countries), or that at the end of 50 years, a party wishing to do so may request that the subject be discussed within the framework of a specific conference. But for a change to take place, the agreement

Fig. 1 – **Land Claims frozen by the Antarctic Treaty in the area lying south of 60°S latitude.** ■

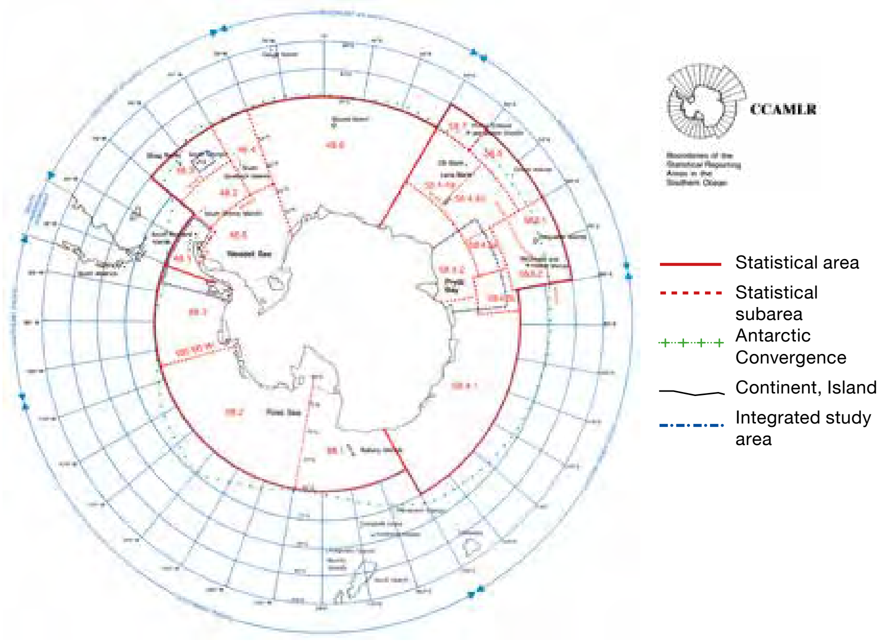

Fig. 2 – **Area of application of the Convention on the Conservation of Antarctic Marine Living Resources.** Source: CCAMLR. ■

of the majority of the CPs, including three-quarters of the states that were CPs at the time of the adoption of the Protocol (there were 26 in 1991) and its entry into force is subject to ratification by three-quarters of the CPs, including all the states who were CPs at the time of adoption of the Protocol (*i.e.* at least 26 countries). In other words, the drafters of the Protocol have taken such precautions to ensure its robustness, so that any modification of its content from 2048 remains highly unlikely.

But Antarctica has other resources now being exploited: marine living resources. In response to the growing commercial interest in krill and the overexploitation of several marine species in the past, CCAMLR was established in 1982 with the aim of conserving these resources (Fig. 2). It now has 25 members and 11 adhering countries. It is applicable to all populations of fish, molluscs, crustaceans and seabirds encountered south of the Antarctic convergence. Cetaceans and seals are covered by other conventions (the International Convention for the Regulation of Whaling and the CCAS). CCAMLR adopts an ecosystem-based management approach, which does not exclude exploitation, provided it is conducted in a sustainable manner and takes into account the effects of fishing on other components of the ecosystem.

In 2009, the first Marine Protected Area (AMP) on the high seas, covering 94,000 km^2 on the southern shelf of the South Orkney Islands, was born. CCAMLR then proceeded to propose the classification of other MPAs. In October 2016, member countries agreed on a proposal by the United States and New Zealand to establish an area of 1.55 million km^2 in the Ross Sea. Some activities will be limited to meet the specific objectives of conservation, habitat protection, ecosystem monitoring and fisheries management. Seventy-two percent of the MPA will be a 'catch-free' area, where all fishing activity will be prohibited, while in other areas fish and krill fishing will be permitted, but only for the purpose of scientific research. Negotiations are continuing on other proposals for classification, notably in Eastern Antarctica, a project carried by France and Australia.

This MPAs system on high seas complements a regime for classifying marine reserves in CCAMLR areas under national jurisdictions. In this respect, the extension of the French Southern and Antarctic Lands in December 2016 makes it one of the World's largest MPAs on the islands around Crozet, Kerguelen, Saint-Paul and Amsterdam (665,000 km^2).

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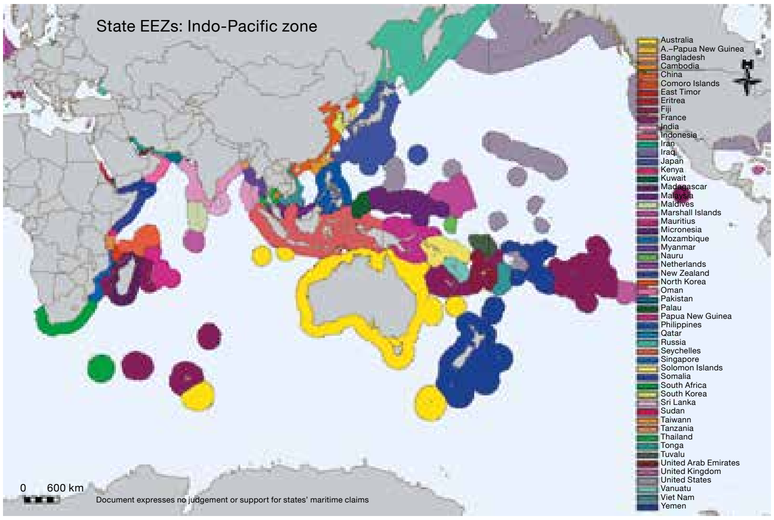
8. The international law of the sea in 2017

Florence Galletti

What is the law of the sea?

What definitions of the ‘Law of the Sea’ should we adopt, if we take the term ‘sea’ to mean the stretches of salt water that communicate freely and naturally around the world? According to Belgian legal expert Jean Salmon, it means all rules of international law relating to the delineation and legal status of maritime spaces and to the activity regime within the marine environment. However, for Polish legal expert Jan Łopuski, the Law of the Sea is of a more strategic nature: it regulates the relationships between states concerning the use of the sea and the exercise of their powers over maritime spaces. As a branch of international law, it brings states and international organizations face to face. It differs from maritime law, which is defined as all the legal rules for private interests operating at sea.

The Law of the Sea has a territorial aspect: it defines the usable spaces and attempts to organize the secure distribution of different parties’ rights over these spaces. The map of maritime zones defined by the United Nations Convention on the Law of the Sea (UNCLOS), common law or international rulings marks out established spaces. These include internal waters, territorial waters, contiguous zones, exclusive economic zones (EEZs), continental plates, the high seas, the international seabed, and their subdivisions (fishing zones), or special legal spaces (islands, bays, straits, international canals, archipelagic waters…). The Law of the Sea also has a functional aspect: it indicates how usages should be allocated (transit passages, vessel circulation, fisheries and economic exploitation of maritime spaces or resources). It sets out who has access, exploitation and trade rights for these spaces and resources, but it also reminds users of the obligation to protect certain ecological services rendered. On this point, the service provided by fishing resources has been almost the sole focus of attention, except for the fight against pollution, as shown in the text of UNCLOS, which entered into force on 16 November 1994. Today, the challenge is to ensure that this text produces responses to issues regarding the ecology of ecosystems, their conservation and their exploitation.



Not all of the maritime delimitations shown are recognized by international agreements, and some of them are subject to disputes between states. This document is without prejudice to Member States’ sovereignty, and expresses no support for any claim.

Simplified representation of marine water zones covered by the national EEZs. Map created using ThemaMap. © F. GALLETTI and G. DOMALAIN, IRD, 2015. ■

An environmentalist turn

The new Law of the Sea (post-1982), was discussed and compiled with a dual objective: to organize the economic development of states and to resolve interstate conflicts. It is not only concerned with exploitation, but also with conservation and that enigmatic aspiration: sustainability. This reveals that the Law of the Sea and marine environmental law are separate, raising questions about their coordination.

Environmental law approaches the sea with the aim of protecting the natural environment. Although controlling pollution remains at the forefront, this law has recently developed to protect sections of the coast or of coastal zones. It is better known for its protection of (certain) species than for its protection of spaces. Its applications remain notoriously insufficient on the coast, and even more so in the EEZs, while the Law of the Sea gives the state great powers to act regarding its internal waters and its territorial waters. This allows the multiplication of instruments for ensuring that biological diversity stays healthy enough to maintain itself and support exploitation. One such instrument is the establishment of marine protected areas (cf. VII.11).

This brings us to the issue of preserving the biological capacity of environments in waters outside of national jurisdiction (over 200 nautical miles from the coast), and in the benthic zone (over 200 or over 350 nautical miles, depending on the location). This is an important issue, given the depletion of natural biological resources and minerals, and the increased consumption needs. In these waters, the ecosystems are geographically distant from the coasts, which adds to their difficult legal situation. Matters such as the capacity of the Law of the Sea to establish (or simply not oppose) crucial protections for the operation of marine ecological networks or corridors required by migratory or not entirely sedentary species illustrate the level of thought and intelligent development required.

The existing legal framework

Zones outside of national jurisdiction are referred to as the 'high seas' (for the water column alone). They are subject to great freedom of use (fisheries, shipping, navigation, laying of cables...). However, fishing freedom is tempered to varying degrees by the existence of regional fisheries management organizations, which can influence the individualistic fishing behaviour of certain states.

The ocean floor (beyond the legally defined continental plates) is considered an 'international deep-sea zone'. Access to its mineral resources is regulated by the International Seabed Authority (ISA). The ISA's initial task was to issue exploration licences for mining activities, but it has also added requirements to evaluate the environmental consequences of these activities for the geological and biological sites that the licenses cover.

There is a clear need for legal reform beyond zones of jurisdiction. From 2018, this reform should lead to a binding UN text covering six key points: the legal authorization of zonal management instruments, including marine protected areas; access to the marine genetic resource; illegal, unreported and unregulated fishing; environmental impact studies; transfer of knowledge on marine technologies; and finally, the sharing of the benefits and advantages (monetary/non-monetary) of marine resource exploitation. If this agreement comes to fruition, the necessary framework for legal cooperation will require more than just instruments for protecting marine zones, applied in national waters by a state which is more diligent than others.

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9. Marine biodiversity law in areas beyond the limits of national jurisdiction

Bleuenn Guilloux

Marine areas beyond the limits of national jurisdiction account for two thirds of the seas and oceans. They correspond to the high seas (water column) and the area (the seabed and ocean floor and subsoil thereof), two international spaces with distinct legal status, but which can be understood as 'global commons', inappropriable and unclaimable, open to all States for legitimate and peaceful purposes. These spaces, respectively defined in contrast to national marine spaces, are often described as the last pioneer front. They are the subject of multiple and contradictory stakes for States and their nationals. Technologically advanced and intensive methods of extraction of biological and mineral resources are prevalent and have resulted in a significant decline in biodiversity, with no single or binding response of international public law in terms of sustainable use and conservation.

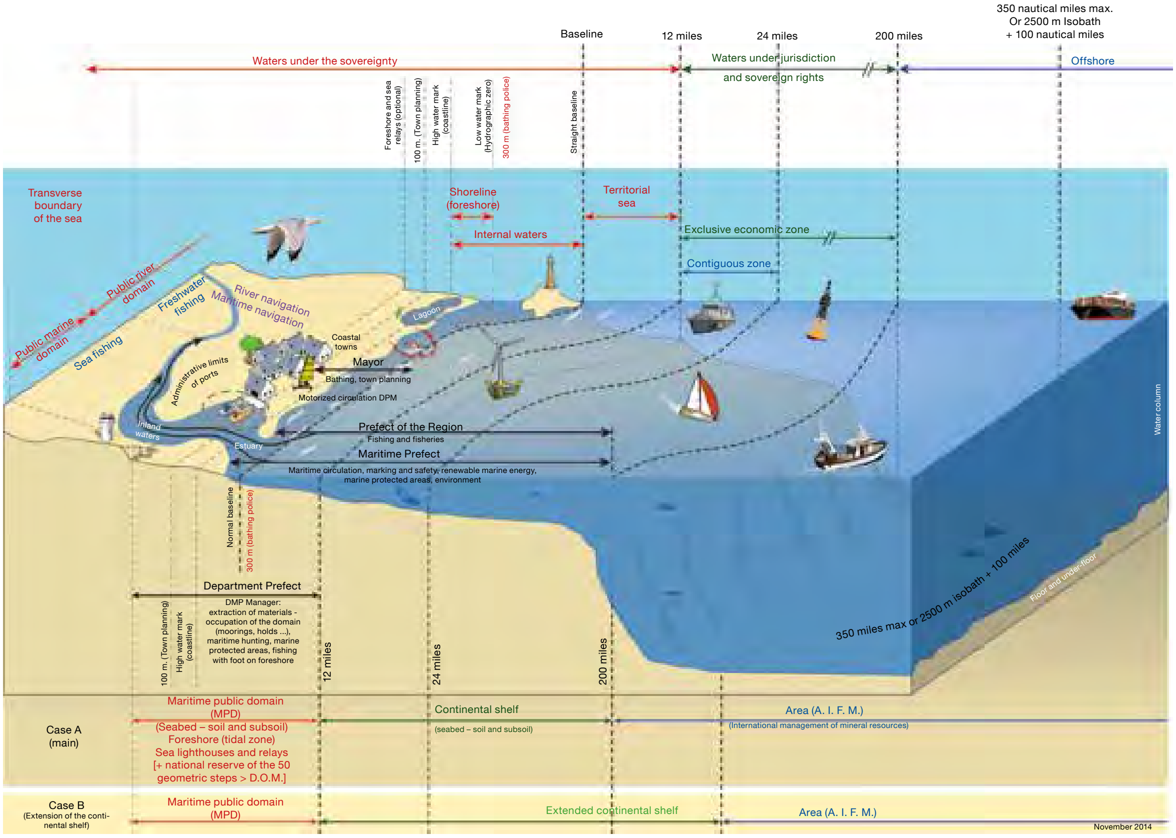

Figure illustrating the legal delimitation of marine spaces and interconnections between marine ecosystems. Source: Agence des Aires Marines Protégées, 2014. ■

Existing international and regional frameworks

Marine biodiversity in international spaces falls under 1982 United Nations Convention on the Law of the Sea (UNCLOS, which came into force in 1994, with currently 168 States Parties) and regional conventions. UNCLOS sets out the spatial framework within which maritime activities are carried out (fishing, navigation, scientific research...). Whether on the high seas, subject to the principle of freedom, or in the zone whose mineral resources are the common heritage of humankind, the use of biological resources remains free. However, this freedom is not without legal limits. UNCLOS provides for obligations to manage and conserve biological resources and to protect and preserve the marine environment in a context of increasingly scarce exploited living resources, and the destruction of their habitats. These obligations relate primarily to the flag State, but gradually found an interpretation at regional level through common management by coastal States of specific ecosystems, such as regional seas (for *e.g.* 1976 Barcelona Convention for the Protection of the Mediterranean), and the regulation of certain exploited species, such as fisheries resources (for *e.g.* 1966 Convention for the Conservation of Atlantic Tunas).

However, the current international and regional legal framework is not complete. Despite the development of an integrated approach since the 1990s, it still only applies to specific areas, species or activities. The distinction between the high seas and the zone illustrates the limits of the legal approach to ecological reality and the development of new uses, such as bioprospecting.

Towards an international agreement

In the early 21st century, the fragmentation of the existing law, the erosion of marine biodiversity combined with a better understanding of it, the increasing value associated with genetic resources of species (microorganisms, symbiosis...), or distant ecosystems (hydrothermal vents, deep corals, cold seeps...) have demonstrated the need for states to negotiate an international agreement on the sustainable use and conservation of biodiversity beyond the limits of national jurisdiction.

After more than ten years of discussions, the European Union, the Group of the 77, China and Mexico, joined by New Zealand and Australia, in 2011 outlined the possible content of such an UNCLOS implementing agreement. Four themes emerged: marine genetic resources, marine protected areas, environmental impact assessment and capacity-building, and technology transfer. After intense negotiations, UN Member States reached an historic decision in January 2015 by recommending to the United Nations General Assembly (UNGA) to open international negotiations by 2016. To this end, the UNGA has established a preparatory committee bringing together States, representatives of UN specialized agencies, observers and civil society to make substantive recommendations to the UNGA by the end of 2017. By September 2018, UNGA will decide on the convening of an intergovernmental conference to consider the committee's recommendations and to draw up a binding agreement.

If states have reached a compromise, they are still divided on the legal status of marine biodiversity. Developing countries and China support the idea of broadening the scope of common heritage of humankind to biological resources, while some developed countries favor a liberal position (the United States, Russia, Canada, Japan, Iceland, Norway and South Korea) and remain reluctant to reach an overly elaborate agreement, arguing inter alia that it could interfere with existing regional and sectoral agreements. The EU defends an intermediate position through the development of a mechanism on access to genetic resources and the fair and equitable sharing of benefits arising from their utilization.

More than thirty years after the signing of UNCLOS and in a context of retreat into sovereignty and creeping commodification of life, the challenge of such an agreement lies in the development of a legal model capable of ensuring a better knowledge and protection of marine biodiversity for the benefit of mankind as a whole.

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10. The ecosystem approach: the fisheries' silent revolution

Philippe Cury and Didier Gascuel

Fishing has a direct impact on the resources being exploited, but also indirect effects on other species and on marine habitats. Overexploitation of predator fish (tuna, cod, grouper...), or sharks, results in unstable ecosystems. Forage fish such as sardines, anchovies or herring are caught in large quantities but are lost prey for predators including birds, mammals or larger fish. On the other hand, discarding of non-marketable species impact marine biodiversity. Finally, dredging and trawling damage the seabed and have significant effects on the health status of ecosystems. To be added to the ecosystem impacts of fisheries, are other anthropogenic impacts, including the destruction of certain habitats (regression of wetlands or mangroves) and biological pollution (invasive species, cf. VI.8). Climate change also affects the dynamics of marine resources (cf. VI.3). The distribution area of many species is shifting towards the poles under global warming, while ocean acidification is destroying corals and altering plankton productivity (cf. II.9). Ultimately, it is the overall properties of ecosystems that may be affected, including productivity, functional biodiversity and resilience.

The ecosystem approach to fisheries aims to reconcile biodiversity conservation, fishing activities that respect all the components of ecosystems and habitats, while maintaining catches and jobs at a high level. a) Colony of Acropora pulchra. © A. KOK. b) Fish for bouillabaisse on the Old Port of Marseille. © R. SMALLKAA. c) The 'Pierre Alain Atao' sardine boat entering the Concarneau seaport. © Pline. ■

Reconciling exploitation and conservation

A global vision recently imposed itself along with the Ecosystem Approach to Fisheries (EAF): the sustainable exploitation of resources, respectful of marine ecosystems. The EAF promises to reconcile the exploitation and conservation of all species, based on the ecosystems, now recognized as the appropriate scale for the integration of scientific knowledge and for management. The EAF emerged with the 1992 Rio Declaration (Agenda 21) and the FAO Code of Conduct for Fisheries in 1995. The role and importance of the EAF was recognized by 47 countries at the Conference on Responsible Fisheries in Marine Ecosystems held in Reykjavík in October 2001.

The EAF now has very direct impacts on fisheries management in some countries including South Africa, Australia, and the United States. In Europe, it is included in the texts of the Common Fisheries Policy (CFP), but the implementation process is slow and tentative. For the past 50 years and still today, fisheries management has been based on scientific advice, which is based on a 'single-species' approach. Fishing quotas are calculated on a stock-by-stock basis (for North Sea cod, Bay of Biscay anchovy...), seeking to ensure the ecological sustainability of each species, but ignoring the complexity of marine ecosystems.

The EAF is, or should be, a process of continuous improvement that changes our relationships with nature and with the governance of the oceans. The international commitments made at the World Summit on Sustainable Development in 2002 in Johannesburg or at the convention on biodiversity in Nagoya in 2010 require countries to '*incorporate ecosystem considerations in fisheries management*.' In concrete terms, the countries pledged to restore collapsed fish stocks if possible by 2015, or by 2020 at the latest, and to establish a network of marine reserves covering at least 10% of the ocean surface area by 2020.

European directives also refer to the need to '*minimize the impact of fishing on ecosystems*.' Behind this expression is actually a major issue. In the face of the complexity and unpredictability of ecosystems, it is necessary to implement a precautionary approach that not only defines maximum permissible impacts, but develops a culture of continuous research for a minimum impact. This concerns, for example, the optimization of catch sizes, fishing technologies, fishing seasons and fishing areas. Overall, it is possible to fish better, or even more, but by impacting less.

The role of science

The role of research is a key in the implementation of the EAF. For scientists responsible for formulating advice and management recommendations, this approach leads to a profound renewal of the fields of research. It is no longer a matter of analyzing and modeling the dynamics of exploited stocks, but of understanding the multiple interactions that determine the functioning of marine ecosystems and exploitation systems. Major scientific advances have been made in recent years in the ecology of interactions. Scenario building for the evolution of socio-ecosystems in the context of climate change has been revolutionized by new modeling techniques. Ecosystem simulation models that combine climate change, changes in the biogeochemical productivity of the oceans and exploitation of human populations are also being developed with fine three-dimensional spatial and temporal resolution. The approaches 'indicator' makes it possible to better evaluate the economic and ecological performance of the different fishing methods, with a view to fleet-based management. These scientific advances are powerful tools, but are still rarely used to improve the operational management of marine resources.

These complementary initiatives will make it possible to implement the ecosystem approach in an increasingly integrative framework and will enable the sustainable exploitation of marine ecosystems in a context of increasingly pressuring and complex issues.

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11. Marine protected areas

Joachim Claudet

The first terrestrial protected areas appeared between the late 19th and early 20th century. They were established to protect part of nature from changes caused by human activities. Freud would see in these creations a perfect parallel with the creation of the mental realm of phantasy, '*withdrawn from the reality principle*'. In Freud's opinion, '*a nation whose wealth rests on the exploitation of the produce of its soil will yet set aside certain areas for reservation in their original state and for protection from the changes brought about by civilization.*'

Awareness of human impacts on the marine environment emerged later. In 1883, 10 years after the creation of the Yellowstone protected area, and while the American bison and homing pigeon were close to extinction, Huxley said in his inaugural speech to the Fisheries Congress that '*all the great sea fisheries, are inexhaustible; that is to say, that nothing we do seriously affects the number of the fish. And any attempt to regulate these fisheries seems consequently, from the nature of the case, to be useless.*' Thanks to archaeological and historical reconstitutions, today we know that this is not the case. Awareness of the need to protect the marine environment emerged after the observed restoration of fishing stocks in the North Sea, after the interruption of fishing during World War II.

Today, there are more than 11,300 marine protected areas (MPAs) around the world. They are used to protect biodiversity and resulting ecosystem services and to manage the uses that are made of them (cf. V.3). Several types of MPAs coexist: fully protected areas, where all types of destructive uses (such as mining) and extractive uses (such as fishing) are prohibited; and partially protected areas, where certain extractive activities are permitted and regulated. Multiple-use MPAs can combine fully and partially protected areas into several zones.

The benefits of MPAs

The benefits of fully protected areas are now well established. They may be ecological, fisheries-related or socio-economic in nature and extend beyond the boundaries of the protected area. Within fully protected areas, ecological benefits begin as soon as fishing ceases, when fishing mortality is eliminated, allowing targeted individuals to live longer. In the short term, habitat quality is improved, fish density and size increase, which in turn leads to an increase in individual and reproductive biomass (Fig. 1). In the medium and long term, the size and age structure of pre-harvested populations are restored and spawning activities increase. Since fishing has historically targeted higher trophic levels, species with the strongest responses to integral protection are predators of higher trophic levels. Consequently, an indirect effect of protection is a trophic cascade in which apical species in the food chain (such as carnivores) regulate the densities of basal species (such as primary produ-

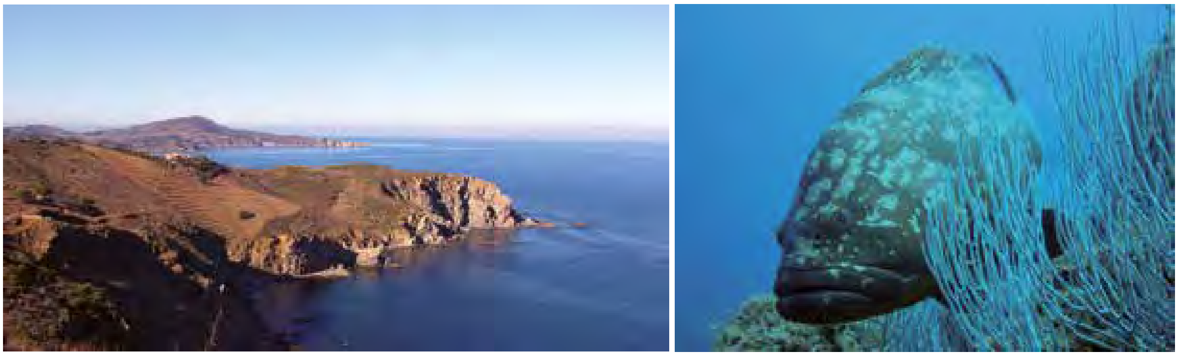

Fig. 1 – **On the left, the Cerbère-Banyuls Natural Marine Reserve.** On the right, a grouper in the fully protected area of the Cerbère-Banyuls Natural Marine Reserve. © A. CARO. ■

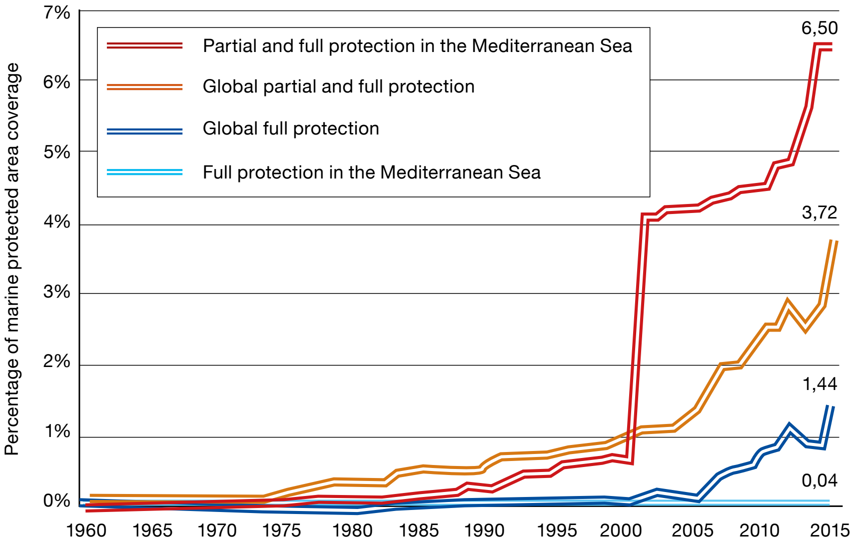

Fig. 2 – **World and Mediterranean coverage of fully and partially protected areas.** Cover of marine protected areas increases over time, but mostly as a partially protected status, which provides fewer benefits than full protection. Source: *La Science des aires marines protégées*, 2016. ■

cers) through intermediate consumers (such as herbivores). This restoration of predator-prey interactions within fully protected areas has in many cases reversed negative regime shifts.

All these benefits are all the more important as the fully protected areas are large, protected for a long time and that compliance is strong. Moreover, once ecologically efficient, these areas can feed the surrounding fishing grounds and ecosystems through two mechanisms: exportation of adults through movement across the fully protected area's boundaries can directly contribute to fishing catch; and the export of eggs and larvae can repopulate the surrounding areas. When properly managed and well integrated into the local socio-cultural landscape, fully protected areas can generate economic benefits greater than their costs by the previously described spillover effects. For example, a study of 12 fully protected areas in Spain, France and Italy showed that revenues generated from fishing and scuba-diving around fully protected areas were on average more than twice as high as their management costs.

The importance of full protection

Although they are numerous, MPAs cover only 3.7% of the world's seas and oceans. In addition, two thirds of the protected area benefit from partial protection only. The situation is even more extreme in the Mediterranean region, with more than 6% under partial protection and only 0.04% under full protection (Fig. 2). Partially protected areas are very useful for the development of more environment-friendly uses and for dialogue between different sea users. However, the ecological, fishery-related and socio-economic benefits of full protection have been demonstrated to be lower, if not non-existent, in partially protected areas. Although the need for protection is very high in coastal areas where such measure prove beneficial in many ways, it is in such areas that the resistance to the establishment of full protection is the strongest, since users do not always understand the medium-terms benefits of protection that short-term changes in their behavior may bring about when enforced. Since most States have pledged to protect 10% of their territorial waters (Sustainable Development Goal No. 14 and Aichi Objectives No. 11 of the UN Convention on Biological Diversity), a major current trend is the establishment of very large, fully protected areas, around small or uninhabited islands, which have to be surveilled by satellite.

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12. Planning the marine space

Yves-Henri Renhas

The need to protect the ocean and its inherent biodiversity is widely recognised. However, in protecting the marine environment, we should not overlook the populations whose livelihood depends on it and the economic activities that allow them to survive and prosper.

The purpose of maritime spatial planning is to accommodate the continuation and further development of economic activities without hindering efforts to improve the ecological condition of the ocean. It involves not only assessing the impact of new human activities before embarking upon them, but most importantly, systematic planning for the future, so as to anticipate potential conflicts between the activities themselves on the one hand, and with the protection of the environment on the other. In other words, maritime spatial planning is a forward-looking process of geographical and environmental organisation of human activities at sea.

Preventing conflicts of use

Once, there were no human activities at sea. Then coastal peoples went there to find food, and trade and maritime transport developed. Empires unleashed their military might there. The sea was not occupied, however, but simply criss-crossed by sailors (cf. IV.2) and worked by fishermen (cf. V.9).

The long-term occupation of the sea began much later, with the operation of offshore oil wells. It wasn't until the start of the 21st century, and the construction of wind turbines that conflicts arose for permanent occupancy of the space, pitting the newly arrived energy operators against the age-old seafarers (engaged in fishing and maritime transport). Marine wind turbines are making a significant contribution to the energy transition towards a low-carbon economy, however.

The need to protect the marine environment led to the creation of jointly managed marine parks and 'Natura 2000' marine protected areas which may be subject to specific regulations in order to safeguard their flora and fauna. There has been wide-ranging consultation every time a Natura 2000 area or a zone reserved for wind turbines has been delineated, at intervals, but there is no specific information on plans for future projects. This source of this overview for the present and the future is government-led maritime spatial planning involving consultation with stakeholders. The overview will help industry to plan its activities, and other users, particularly fishermen, to determine the areas where they can continue to ply their trade, while scientists can explore those locations where protected marine areas could be created.

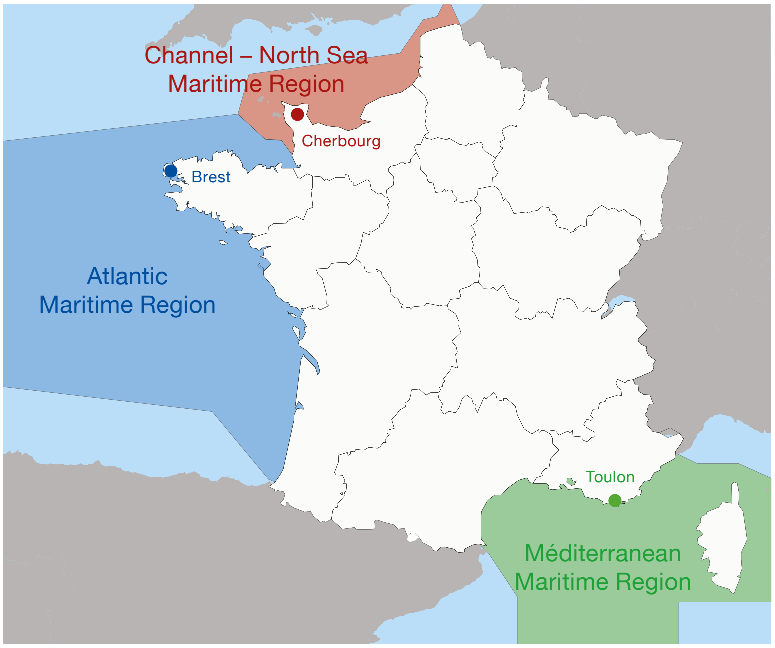

Fig. 1 – **The maritime authority's areas of responsibility in the three maritime regions.** © Cedre. ■

Fig. 2 – The coasts of France are a popular location for pleasure boating. © H. FOURNIAL. ■

An integrated European maritime policy

Aside from the Common Fisheries Policy, which falls within the exclusive jurisdiction of the European Union, there is a maritime aspect (including transport and the environment) to several of the areas in which the Union and the member states have shared competence. Commission Communication 575 of 10 October 2007 proposed an integrated maritime policy, a political commitment that was reaffirmed in the Limassol Declaration of 8 October 2012 by the ministers responsible for the policy. Accordingly, the protection of the marine environment is covered by the Marine Strategy Framework Directive 2008/56/EU of 17 June 2008 and maritime spatial planning is covered by Directive 2014/89/EU of 23 July 2014.

Certain European Union policies (such as the environmental protection policies) already include a maritime dimension. There are two directives in particular that set out the need to protect certain bird species and certain types of landscapes or seascapes, characterised by their ability to accommodate certain types of flora or fauna (their habitats). Each member state has to define special conservation areas (under the Habitats Directive) including a sufficient body of habitats to be protected and habitats containing species that need protection, as well as an adequate number of special wild bird protection areas (under the Bird Directive) for rare or endangered species, as part of the Natura 2000 network.

Maritime policy in France

Centralised harmonisation is needed for the constituent elements of France's maritime policy, particularly those with at least a partial impact on the maritime, energy, transport, fisheries, defence and environmental spheres. The legislation drafted following France's Grenelle de la mer environmental summit on the ocean helped in the introduction of a system of consultation for the sea and the coastline. A national council of the sea and coastal areas (CNML) was set up, with a membership comprising elected representatives, experts, economic and social partners and representatives from environmental protection agencies. Sea basins were defined: *Manche Est – Mer du Nord* (Eastern Channel-North Sea), *Nord Atlantique – Manche Ouest* (North Atlantic-Western Channel), *Sud Atlantique* (South Atlantic) and *Méditerranée* (Mediterranean). A consultative sea basin maritime council (CMF) was set up for each seaboard, with meetings attended by the stakeholders and co-chaired by a specially appointed regional coastal prefect and the relevant maritime prefect, who represents the state's authority at sea (the maritime prefectures are based in the major military ports of Cherbourg, Brest and Toulon). The CMFs provided a forum for the consultation planned in connection with the implementation of the Marine Strategy Framework Directive.

For each sea basin, the plans that derive from the maritime spatial planning process break down the guidelines developed at national level and articulated in the French national sea and coastline strategy. They are the result of the delicate balance between the interests of different branches of activity, the requirement to protect the environment, local interests and the general public interest, which remains the responsibility of the state. High quality plans and stakeholder buy-in will be key for the sustainable development of the maritime economy.

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- PART EIGHT -

The ocean: what lies ahead?

Previous page:

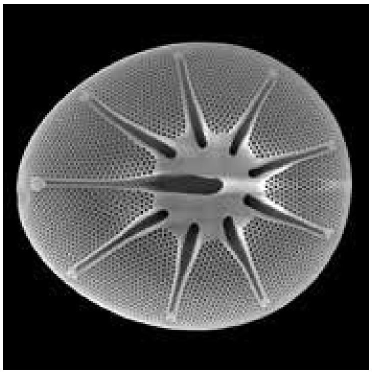
A fracturing ice cliff in Commonwealth Bay to the east of Adélié Land, Antarctica. © E. AMICE / LEMAR / CNRS Photo library. ■

1. The ocean, crucial for our future

Denis Lacroix and Thierry Pérez

If the unit used to measure the 'value' of the ocean were world gross value added, it would be worth a modest 2.5% of the total. However, if we refer to the value of the ecosystem services rendered to the planet, then its value is immeasurable. While our knowledge of the services rendered by the ocean is still far from complete, how can we calculate the little that we do know about its regulating effect on the climate, its capacity to transfer heat flows, its function as a carbon sink or its role in oxygen production? Marine biological resources have been feeding humans for thousands of years and the power of many ecosystem services is still to be demonstrated, for example the equivalent to pollination in the sea or the importance of 'natural' bioremediation of the many pollutants continuously deposited in the marine environment. High-level political debate on the future of the planet began with the climate. This can be summarized in a question that establishes something of a vicious circle: 'How do we avoid the unmanageable and manage the inevitable?' That debate was then extended to include biodiversity protection or 'How do we counter the sixth mass extinction of species now under way?' As a result of scientific work, international conferences, and sometimes media coverage, there has been gradual recognition of the importance of the ocean.

There is still a very long way to go, however, for three main reasons. Firstly, the ocean's characteristics, resources and functions are still little known, little understood and insufficiently measured. Next, it is a vast space that is difficult to access, with complex physical, chemical and biological dynamics, which does not facilitate overall understanding of its habitats, the processes at work and its potential resources. Finally, it is subject to little – if any – management and the short-term and long-term challenges of the sustainable (or non-sustainable) exploitation of its riches are now a bone of contention. The majority of the ocean's surface is deemed 'international waters' with a weak rule of law despite the many stakeholders exploiting the ocean in different ways, most often with little concern for sustainability and paying little heed to the fragility of this asset that has been handed down and shared for thousands of years. The many different approaches to the ocean and its potential futures, simply over our own century, are illustrated in this chapter from a variety of viewpoints and areas of study, from the Arctic to the Mediterranean, from marine biomolecules to ecological engineering, from tourism to protection, from the global perception of the ocean to opportunities stemming from Sustainable Development Goal 14, explaining the wealth of possible scenarios for marine socio-ecosystem evolution. What is important is not so much listing and understanding all of this, but increasing awareness of the crucial role the ocean plays in our future.



One of the keys to evolution at the macro-scale of the ocean surely lies in understanding the role of micro-organisms such as this diatom algae *Asteromphalus flabellatus*? © Ifremer / E. NÉZAN, N. CHOMÉRAT. ■

There is also a race against the clock as certain irreversibility thresholds have been identified, such as ice melting and the consequences that it may have on ocean physics, the biodiversity found in the polar zones, and the impairment – or even loss – of certain ecosystem functions. Scientific knowledge is also used to inform leaders on the consequences of the choices to be made over ocean exploitation and management and the preservation of its functions. Every day, science proves that the ocean must come at the top of the list of critical issues if our aim is to secure a thriving, resilient earth, in other words, a 'human', well-functional blue planet for the long term.

2. A forward-looking perception of the ocean

Denis Lacroix

The ocean is often associated with the innumerable, the infinite, and the timeless. Its perception and study are difficult for scale, permanent mobility and complexity reasons. While some marine phenomena seem immutable and predictable, unpredictable change often characterizes this four-dimensional space. Since 'prospective view' is defined as reflection on the evolution of a system over the medium and long term, with the right to introduce breaks, can this 'intellectual indiscipline' (H. De Jouvenel) be of help in the governance of this immense, little known, partially understood and yet essential environment for the equilibria of this planet? Since the human being is the first factor in the changing of this environment, it is useful to see how the ocean has been perceived, depending on cultures and times, by those interested in the future.

A caravel, a ship designed for the great maritime expeditions of the 16th century. Map of M. Prunes, 1563, Museo naval. Madrid. ■

A mythical and (already) strategic space

The ocean (the sea in its broad sense) has been, since its original waters mentioned in the Bible, a place of legends such as that of Poseidon/Neptune's kingdom or of the Polynesian god Ruahatu, the master of the atolls' destiny. It is associated with the sacred, but also with all kinds of threats: drowning, storms, currents, reefs, monsters from the depths, unfathomable abysses where even sirens can be dangerous (Ulysses). However, as soon as the first boats were designed, the ocean became a space of exceptional interest for three functions: fishing, trade and war. Several centuries before the Common Era, antiquity strategists began to reason in terms of war fleets, for they intuitively understood that "whoever owns the sea owns the land". That is how Salamis (–480) marked the end of the Persian conquest in the Aegean, as Actium (–31) ended Pompey's Imperium, as Rome ultimately triumphed over Carthage by capturing its maritime network.

However, building war fleets takes years, is expensive and requires considerable infrastructure (900 vessels engaged at Actium). So foresight is crucial. Thus, according to the usages of the marine world, it is the military naval challenges that first structured this long-term vision (cf. IV.11).

Trade and conquests

From Ancient times to the Renaissance, many maritime expeditions extended the limits of the 'known' world (a relative concept). The Vikings discovered North America. Seven Chinese fleets explored the Indian Ocean and the Red Sea from 1403 to 1433. But these maritime exploits ultimately came to nothing, for there was no long-term vision, no stable political will, no regularity in resources, in short, no prolonged prospective view of a strategy. In the 15th century, Henry 'The Navigator', Prince of Portugal, conscious that the Ottoman power would block any navigation activity in the eastern Mediterranean, wanted to find a passage to India by sea and to even more land. This would require designing a ship suitable for long ocean voyages. In 1418 he created 'the school of Sagres', bringing together the best carpenters, cartographers and pilots. The result was the creation of the caravel, the perfect synthesis of the marine knowledge of the time. It paved the way to the golden age of maritime expeditions: Columbus, Vasco de Gama, Magellan... The competition between European powers was launched. Maritime routes and ports of call became major stakes in trade and in the conquest of immense territories, East and West.

The World Imperium requires ocean control

Advances in shipbuilding, the globalization of trade *via* maritime routes and the strategic advantage that enables control of such routes led the great powers to acquire commercial and military fleets that are both numerous and organized. Britain's highpoint was reached during the reign of Queen Victoria: '*Britannia rules the waves*', from London to Sydney. Scientific knowledge advanced through maritime expeditions from the 18th century, not without ulterior motives having to do with political and commercial influence. Jules Verne wrote 20,000 leagues under the sea in 1870 and the first world oceanographic expedition by the Challenger took place from 1872 to 1876.

In 1890, the American admiral Alfred T. Mahan theorized the concept of world power and its corollary, naval power. His long-term vision of the United States' key role led to the construction of the most powerful navy of all time. Today, the same logic persists: China wants to become a major naval power, which also implies a vast program of ocean studies.

New usages, new visions

In the 20th century, the usages of the ocean and within the ocean are increasing including the extraction of oil, gas, aggregates; fishing, aquaculture, mass tourism, new products and molecules. Knowledge of the ocean is expanding and reveals that the Ocean is the 'radiator' of the Earth (cf. I.3), that it contains exceptional biodiversity (cf. III.17), but also that it is acidifying (cf. II.9) and that many marine ecosystems are being disrupted (cf. VI.9). These findings should be encouraging longer-term visions. However, it was not until the Conference of the Parties in 2015 that the importance of the ocean was recognized and appeared among the UN's sustainable development objectives (cf. VII.4). But a recent review of 99 studies on environmental scenarios up to 2100 showed that the ocean is never taken into account as a major factor of evolution; the consequences of the 307 scenarios studied rarely involve the ocean and, when they do, it is always its degradation.

Prospective analysis must raise awareness at all levels of responsibility that perceptions of the ocean have to evolve if we are to preserve this vital environment for humankind through the sustainable management of its resources, like the main climatic balances.

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3. What are the challenges facing ocean-climate research?

Pascale Delecluse

To understand the role played by the ocean in climate, we need to understand the time pattern imposed by the scale of the mass and energy that it represents. The ocean moderates the contrast between land and sea, acts as a reservoir for heavy rainfall (such as cyclones and the rains in the Cevennes region of France), contributes to seasonal heat transfer, and so on. However, these involve very short timescales. At climate scale, over periods of a few years to several thousands, the ocean becomes a major protagonist capable of exacerbating energy, geochemical and rainfall imbalances, resulting from its global circulation system with its own pattern of responses to the pressures that are exerted upon it (cf. II.11).

Two distinct time patterns

Surface exchanges between the ocean and the atmosphere drive the formation of water masses that move in response to wind and pressure forces (cf. II.10). These exchanges influence sea state, wave production and chemical concentrations; they are difficult to represent as they encompass a wide range of scales and operate *via* a highly dynamic interface under quite diverse geographical conditions. Furthermore, it is not sufficient to understand the local processes, as exchanges occurring through advection or through turbulent exchange with the surrounding water must also be taken into consideration. Lastly, the ocean is not a passive integrator of the atmosphere; on the contrary, it plays an active role through the impact of its thermal and mass inertia on the overlying air. Both fluids must therefore be studied in conjunction, as they have their own specific dynamics and modify each other in a continuous way.

The last few years have been very productive in terms of our understanding of how the ocean operates and the identification of the processes at play within it. The idea of a stationary flow has been replaced by that of highly variable circulation with a complex vertical structure characterised by reversals of current direction; fields of eddies have replaced our view of the oceans in terms of a river. This new perspective on the sea raises questions on the changes taking place.

The Mediterranean Sea (right) and the Arctic Ocean (left) regions are both subject to particularly close monitoring by researchers, in view of their marked response to climate change. CC0 Public Domain. ■

Impacts on ocean warming

In contrast to the atmosphere, the ocean is essentially vertically stable, being surface-heated. Deep waters are renewed in intense sporadic episodes of cooling, evaporation and freezing during the winter; these form dense water which sinks, thereby enabling deep-water renewal. Most evident at high latitudes, global warming intensifies surface warming, which increases stratification and interferes with deep-water ventilation. Increased stratification has serious implications: it changes the vertical structure of currents and accelerates the propagation of ocean waves; it limits the deep penetration of nutrient salts and oxygen (depleting the environment and creating the risk of anoxia); and it slows down surface carbon dioxide absorption (a warm ocean absorbs less carbon dioxide than a cool ocean). Under these new conditions, the water masses gradually degrade and in particular, the processes of deep and bottom water renewal become less effective, affecting thermohaline circulation and the meridional transport of water, heat and carbon dioxide.

Let's take the example of global warming in the Mediterranean (cf. VIII.11). This sea is an evaporation basin and in winter, it produces the Mediterranean Deep Water, where deep salty water formed in the Levant Basin (the eastern Mediterranean beyond Greece) mixes with the deep waters formed in the Gulf of Lion. An increase in surface temperature creates less dense water, which does not sink so deep, and this may deprive the deep waters of oxygen.

The Arctic region is also subject to close monitoring, where the melting of the polar sea ice affects the regions likely to form the deep waters of the North Atlantic. The reduction in polar sea ice changes the formation zones and impacts their characteristics. One scenario that is cause for concern involves the dramatic lack of deep water formation; this has already happened in the past, when a large volume of freshwater was released onto the surface as a result of iceberg break-off from continental ice cap (a Heinrich event). This would have the effect of shutting down thermohaline circulation and therefore halting the meridional transport of heat towards Northern Europe and the Arctic, resulting in climate cooling.

Oceans under surveillance

The North Atlantic is a key region for future changes. The century-long forecasts made using coupled climate models tend to predict a slowdown in thermohaline circulation over the course of the century. However, the representation of convective processes and the conditions for ocean-atmosphere exchange which trigger them is still very crude, and the observation networks need to be enlarged to enable a better understanding of the speed of the current changes.

Another critical region where monitoring change is important is the tropics, where the two major fluids, ocean and atmosphere, are coupled. It is the focus of major climatic anomalies which have a profound effect on marine and terrestrial environments (cf. II.13). This phenomenon has a critical function, not only redistributing energy between the eastern and western equatorial Pacific Ocean, but also redistributing heat along the eastern Pacific seaboard, where it affects the trophic chains. In a warmer climate than we have today, with an even more stratified ocean system and a warmer atmosphere containing more water vapour, what would be the effect on El Niño? Would it happen more frequently, with greater intensity, as part of a system transitioning towards a new equilibrium? This is the challenging question that research has to address.

Lastly, a critical issue in adapting to climate change is the ability to make forecasts for periods from a few years to several decades. This timescale presents particular difficulties, as it is both sensitive to changes in external forces, such as the increase in greenhouse gases, and to internal variability factors, where the ocean plays a predominant role. If we look at Europe, for example, we need to know whether the North Atlantic Oscillation is in a positive or negative phase, which is heavily dependent on the distribution of the water masses in the Atlantic, from the tropics to the temperate latitudes. This raises the challenge of developing a better understanding of the ocean and its ability to influence the climate patterns that substantially impact our environment.

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4. Scenarios for the evolution of marine ecosystems

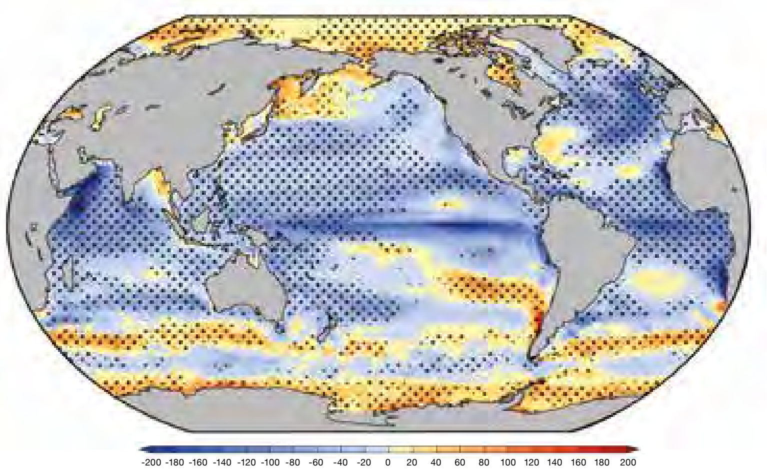
Olivier Maury and Yunne-Jai Shin

The oceans and their abundant biodiversity provide essential ecosystem services. Responsible for the sequestration of 25% of anthropogenic carbon emissions and the absorption of the majority of excess heat in the atmosphere, they also play a major role in the regulation of atmospheric CO_2 and of the climate (cf. II.14). Their exploitation by fishing is a key source of income and protein for a significant part of the global population. However, climate changes threaten these ecosystems and the valuable services they provide. These changes modify the temperature, stratification and circulation of the ocean. They could lead to the expansion of vast hypoxic regions, while the absorption of anthropogenic carbon causes the waters to acidify (cf. II.9). These changes hinder primary production, which is vital for ecosystems and biodiversity. With marine ecosystems being driven towards unprecedented states, scientists are beginning to quantify the future consequences of this for the climate, fisheries and their economies.

Meanwhile, fish is playing an ever-growing role in the human diet, and consumption has now reached 20 kg per person per year. The importance of marine resources for food security has been established, and looks set to grow in the future, with the human population predicted to reach 9.7 billion in 2050. Pressure on marine resources will therefore also grow, while their ecosystems are already weakened by fishing and threatened by climate change. In this worrying context, it is crucial to define scenarios based on integrated models of marine socio-ecological systems. This is the foundation of the work of the IPCC (Intergovernmental Panel on Climate Change) and the IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services), who attempt to anticipate the threats and opportunities generated by the coming changes, and to quantify future vulnerabilities. It is also important to devise prevention, adaptation and governance strategies that will allow us to achieve the ocean conservation and sustainable exploitation objectives set out in SDG 14 (cf. I.14).

More stratified and less prosperous oceans

The warming of the atmosphere is transmitted to the oceans, meaning that their surface temperature could rise by 0.7 to 2.7°C by 2100, according to the forecast climate scenario. However, this warming primarily affects the surface layers, which warm up faster than the deep layers, causing increased stratifi-



Predicted change in primary production ($g.C.m^{-2}.year^{-1}$) between the start and the end of the 21st century, for climate scenario RCP 8.5: 'business as usual'. The dotted areas are those where the projection is most robust. According to Pörtner *et al.*, 2014. ■

cation of the oceans. This effect is likely to worsen in the future, particularly at low latitudes.

More stratified oceans will be less prosperous. Water layers of different temperatures, and therefore different densities, limit the ascent of deep nutrients towards the surface, where primary production takes place. This will cause phytoplanctonic production to fall by 9% by the end of the century, according to the worst case scenario used by the IPCC (RCP 8.5). Primary production will fall most at low and medium latitudes, where stratification will increase the most. In contrast, models predict that phytoplanctonic production could rise, sometimes significantly, at high latitudes (Fig.).

Deoxygenated and more acidic oceans

The warming of the surface waters reduces oxygen solubility, while increased stratification decreases ventilation of the deeper waters. It is predicted that by the end of the century, these two phenomena will cause a 1.8 to 3.5% drop in the total quantity of dissolved oxygen in the ocean. This decrease will lead to accelerated vertical and horizontal expansion, particularly in temperate and polar zones, and in oxygen minimum hypoxic zones, which today essentially occupy vast regions in the eastern tropical Atlantic and Pacific oceans. It will also contribute to the multiplication of anoxic 'dead' zones in eutrophic coastal zones, where only certain bacteria can survive.

The oceans absorb a significant portion of atmospheric CO_2. This dissolved oxygen forms carbonates and acidifies the waters. Over the century, the increased presence of CO_2 emissions in the atmosphere could cause a 0.07 to 0.33 unit drop in the oceanic pH. This acidification of the oceans is very likely to have major impacts on many calcifying species. This will modify the structure of ecosystems, particularly that of the coral reefs (cf. II.25), which are already affected by rising water temperatures.

Resource decline and redistribution

Several studies show that the drop in primary production could be amplified at the upper trophic levels. Therefore, the global decrease in primary production would cause a 15 to 25% reduction in global fish biomass by 2100. Moreover, temperature is an essential determinant for the physiology of marine organisms, which can only survive in very specific ranges. Increased water temperatures will therefore profoundly modify their spatial distribution. The tropical waters may become deserted because they will grow too hot. When tropical and temperate species can no longer easily colonize the deeper waters, which are cooler but darker and increasingly deoxygenated, they will be pushed towards the poles, where productivity will increase. Meanwhile, polar species will no longer be able to find a suitable habitat, and risk mass extinction.

Today, it is acknowledged that most marine species will undergo radical changes in abundance, geographical distribution, migratory routes and phenology (cf. VI.9). However, these changes will vary from one species to the next, and between regions. Interactions between species and the composition of communities will be distorted. Fisheries will be forced to adapt. Overall, the tropical regions face the biggest losses. Conversely, new exploitation opportunities may appear in the polar regions, but these will need to fit in with the conservation of threatened species. To understand how our choices today influence the ocean that will support our lives tomorrow, it is vital to define scenarios for marine socio-ecological systems. We must not only warn of the dangers to come, but also devise new paths towards sustainability. The stakes are high: we need to build the knowledge that will allow us to avoid the unmanageable, and equip us to manage the unavoidable.

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5. Protecting the marine environment

Florence Cayocca

Why protect the oceans?

The marine environment is a hidden world. Interest in the sea was for a long time limited to what human societies had to gain from it, namely the marine resources that they could exploit – even more so than for terrestrial environments. It is significant that the need to protect the marine environment was first expressed in regard to the regulation of fishing, which was a result of the United Nations Conference on the Law of the Sea in 1958. The Conference led to the drafting of four conventions, including the 1958 Convention on Fishing and Conservation of the Living Resources of the High Seas. Signatories to the Convention observed that '*the development of modern techniques for the exploitation of the living resources of the sea [...] has exposed some of these resources to the danger of being over-exploited*'. It took several more decades to implement international agreements for the preservation and management of the fishery resource, and there was no discussion of the challenges of conservation and the sustainable use of biological diversity (Convention on Biological Diversity, cf. III.17) until the first Earth Summit in Rio. Going beyond the concepts of habitat and species protection, the Conference of the Parties in Nairobi (2000) addressed the importance of the ecosystem approach and biological connectivity. The need to protect all of biodiversity (including so-called 'ordinary' biodiversity, in contrast to 'remarkable' biodiversity, comprising particular species or certain iconic habitats) was next discussed in 2004, mainly as a result of the creation of instruments 'combining the management of protected area networks, ecological networks and zones which are not part of these networks'. The Global Forum on Oceans, Coasts and Islands, founded in 2002, ensured that matters relating to the ocean were on the agenda for all United Nations international negotiations. The first strategic plan for protected marine areas was adopted in 2007 and the proposal to establish scientific registers of 'ecologically or biologically significant marine areas' (ESBAs) was formally acknowledged in 2009.

Lastly, the Nagoya protocol adopted at the Conference of the Parties in 2010 undertook that 'by 2050, biodiversity [would be] valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people'. The protocol featured the adoption of a strategic plan for 2011-2020 with 20 quantified targets (the Aichi Tar-

Fig. 1 – **Protection is an issue both for coastal zones with a high level of human activity and for the high seas.** Shown here, a pair of humpback whales (Megaptera novaeangliae), a global species present in the waters of the Pacific, the Atlantic, the Southern Hemisphere and the Antarctic. © F. MAZÉAS. ■

gets), including three relating to the marine environment. These are: *i)* to promote the sustainable management of the stocks being exploited, by taking an ecosystem approach; *ii)* to reduce the human-induced pressures on coral reefs and other marine and coastal ecosystems vulnerable to the impacts of climate change; and *iii)* to protect 10% of marine and coastal zones using networks of effectively, equitably managed protected areas.

This international context is reflected at the regional level, specifically through 18 'regional seas conventions and action plans'. These create a framework for technical and scientific cooperation to evaluate the quality of the marine environment, define and qualify the pressures affecting it, and agree on appropriate solutions in terms of strategies, policies and management tools. The work carried out under these conventions is likely to inform European or international legislation.

At the European level, the Marine Strategy Framework Directive adopted in 2008 is now binding on member states. Based on an ecosystem approach, it aims to take the measures necessary for achieving 'good environmental status' for Europe's seas.

The need for global protection

The threats to marine ecosystems are linked to terrigenous pollution (cf. VI.10-12), the repercussions of global change (cf. VI.3) and to activities at sea. Strategies for 'repairing' the marine environment are showing their limitations (cf. VIII.6). Integrated marine protected areas have proven highly effective in helping to reconstitute healthy, productive ecosystems (cf. VIII.5), but they need to be accompanied by management strategies for whole oceans, if more than just a few oases of biodiversity are to be preserved. These strategies must not overlook the protection of the high seas, where the wealth of marine resources is even less visible than in coastal zones (cf. II.20), and such protection is still a matter of international discussion (Fig. 1).

Above and beyond the measures promoted by essential regulation, it is crucial that we are aware of the importance of protecting the marine environment for society's well-being, that we understand the shared interests in this environment and that we become stakeholders in its preservation: the experience of applying measures to manage fishing has shown that they are only fully effective when the professionals themselves are convinced of their importance and fully involved. More broadly, the protection of the marine environment requires concerted efforts. Going beyond the need to involve marine environment stakeholders, marine education areas embody the hope of a better future for the oceans by providing schoolchildren with a small area of sea to manage and involving them in the processes of managing it. These children will be the best future ambassadors for the protection of the marine environment (Fig. 2).

Fig. 2 – **Promoting the issues of protection by involving children: schoolchildren in their marine education area on Ua Pou, one of the Marquesas Islands in French Polynesia. © N. JOB / Heos marine. ■**

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6. Ecological restoration and engineering for sustainable management

Sylvain Pioch and James Aronson

In 2015, 60% of the world's population – 3.8 billion people – lived less than 100 km from the coast. If current demographic trends continue, by 2025 the population of these areas is expected to be around 7 billion (almost twice as many as at present). Along France's coastline, the area of publicly owned coastal land 'reclaimed' from the sea was doubled between 1965 and 1980 (MEDAM, 2015). Provided that we look at monetary indicators alone, rather than any environmental indicators, this socio-economic development has clear benefits. Given the many adverse consequences for the natural environment, the intelligent long-term response is therefore to reconsider our approaches to planning and consumption, measuring the negative as well as the positive impacts of our activities on the ecosystems and natural environment that are so vital to our health and wellbeing. There is also a need for short-term solutions to the degradation to which society is both witness and victim.

Environmental restoration and engineering are practical applications of environmental principles and environmental models for the repair and sustainable management of the environment. They are based on the idea that action is possible in response to the – largely human – degradation of the natural environment. Examples of such applications include the use of seaweed for bioaccumulation in the clean-up and rehabilitation of seabeds polluted by heavy metals (as in Kensenuma Bay in Japan), and the propagation of coral by taking cuttings in regions affected by degradation as a result of natural phenomena such as hurricanes or man-made causes like pollution. This fledgling sector is creating jobs and its worldwide development potential is an average of $100 billion per year between now and 2050 (TEEB, 2010).

Fig. 1 – **Artificial reefs made of limestone boulders to restore the rocky coral substrates, offsetting the impact of marine works to restore the sand along the beaches of the Miami county coastline in Florida, USA.** © K. KILFOILE. ■

Repairing a marine natural environment

Ecological engineering is often confused with ecological restoration. According to Andre F. Clewell and James Aronson (2013), ecological engineering uses living organisms or other biobased materials to solve socio-economic and/or environmental problems, particularly in the short term. In the case of ecosystems shaped by humans (known as 'semi-cultural' ecosystems), there is sometimes a need for regular intervention, to halt or limit the negative impacts of the intensification or extensification of traditional or new human activities, using various tools of ecological engineering (creation, improvement...). The more ambitious aim of environmental restoration, in the marine environment and elsewhere, is to restore an ecosystem that has been degraded or destroyed to its historical trajectory so that it can self-regenerate, adapt and evolve independently following the intervention without the need for subsequent work (SER, 2004).

Can the seabed be repaired, though? Experience shows that it is rare to achieve remediation of 70% of the devastated environment; 90% is exceptional. A proportion of the ecological loss is therefore permanent. This is the case with deep-water corals and with certain seagrass beds, such as Posidonia oceanica in the Mediterranean. Attempts to transplant this underwater flowering plant have met with limited success: a trial that took place in 2005 when the Spanish port of Campomanes was undergoing expansion was intended to offset the destruction of 20 hectares of seagrass. Transplantation of 200 m^2 of posidonia seagrass resulted in a survival rate of just 15%. In Florida, in 1995, an area of 704 m^2 of seagrass (Thalassia testudinum, Syringodium filiforme and Haludole wrightii) was destroyed by a variety of human activities, including uncontrolled anchoring, ship groundings and pollution. After 11 years of restoration work, the success rate in terms of the biodiversity and ecosystem services recovered was assessed at just 50%. The success of these operations therefore seems to be a matter of chance, while their cost is considerable, at between \$0.5 million and \$1 million per hectare.

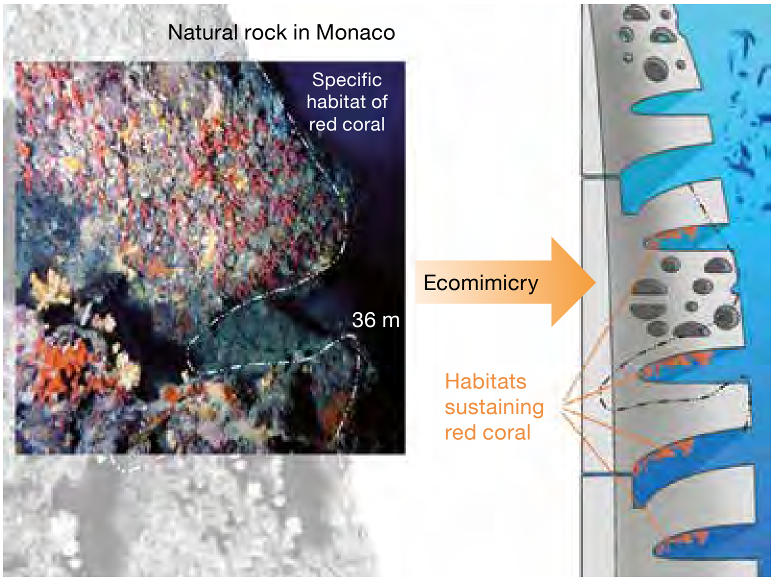

Fig. 2 – **Artificial habitat mimicking the natural habitat (form, orientation, depth and substrate) of red coral caves in Monaco, on the Mediterranean.** Design: S. PIOCH. Layout: J. L. FERON. ■

What kind of nature do we want?

In the face of the current poor performance of ecological restoration and engineering techniques in the marine environment, good sense dictates that many projects should not be authorised. Decision-making has to take better account of the limitations of ecological techniques and the risks of irreversible damage to approve or reject future marine developments. Indeed, if natural history shows us that there are numerous potential 'natural' trajectories for ecosystems, what should be the basic guidelines for public measures to repair natural environments? What kind of nature do human societies ultimately want? Under pressure from accelerated degradation and human environmental processes, how can we identify acceptable (or unacceptable) disruptions from ecosystem changes linked to the increasing human environmental footprint? Lastly, although progress is being made in science and technology, the measures described will only be effective as part of a regulatory framework that is upheld; further, decision-makers must have the knowledge and education to consider long-term economic and ecological gains and losses. The only way to develop the understanding and objective tools needed to analyse the limitations of marine development or to try and better anticipate its impacts, is through increased multidisciplinary research, to ensure that our decisions on whether to create artificial environments are properly informed.

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7. Marine biomolecules: a source of sustainable development

Olivier P. Thomas and Thierry Pérez

'The oceans hold the key to mankind's future': a position shared and voiced today by scientists, economists and politicians alike. It represents the expression of a recent awareness about the value of our natural marine heritage, also linked to the depletion of terrestrial resources and the negative effects of global change (cf. VI.3). In addition to the direct use of fishing resources, new ways of using marine products, biomolecules and/or bioactive substances will undoubtedly contribute to creating new wealth, provided we do not succumb to the pitfalls of unreasonable exploitation.

Marine macromolecules, an old tradition

The search for proteins or peptides from the co-products of fishing is far from new. Currently, their particular amino acid compositions make them popular as food supplements, thanks to their palatability and digestibility. The antioxidant properties of certain compounds from macroalgae also lead to their use as oligo-proteic ingredients in cosmetology (cf. V.12). Meanwhile, the polysaccharides that make up plant cell walls are used by the food and cosmetics industries, for their gelling properties. These two industries also continue to exploit the beneficial properties of marine lipids, and today, after the interest in omega-3 rich fish liver oils, it is microalgae lipids that are being used in animal or human nutrition. We can envisage other biotechnological applications, as for the green fluorescent proteins isolated from the Aequorea victoria jellyfish. This discovery led to the 2008 Nobel Prize in Chemistry and the proteins are now used in most molecular biology laboratories. The exploitation of these macromolecules requires access to significant biomasses, creating a need for environmentally friendly supply solutions. These include using proliferative species and/or non-indigenous species (microalgae, jellyfish, crustaceans), and bio-reactors for single-cell prokaryotic and eukaryotic micro-organisms: systems which allow the production of biomass and potentially stimulate the metabolism of interest.

Natural product chemistry: a new marine el dorado

Marine natural product chemistry and its applications in the pharmaceutical field date back to the 1950s. It quickly became apparent that the chemical component of marine biodiversity was extremely promising, and two 'marine

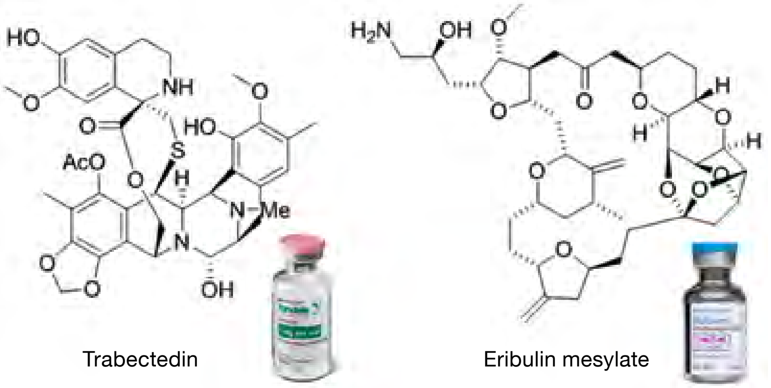

Fig. 1 – Two cancer medications of marine origin. ■

medicines' appeared rapidly: Cytarabine on the anti-cancer market in 1969 and Vidarabine on the antiviral market in 1976. Despite these early successes, big pharmaceutical companies considered this research too risky and insufficiently profitable. This left small and medium sized enterprises to take the lead, for example Pharmamar in Spain (1986) or Nereus Pharmaceuticals in the United States (1988). These companies worked closely with universities, mainly benefiting from their expertise in the natural sciences. Many collection expeditions were organized in all the world's seas, with the aim of screening as many small molecules (also known as 'secondary metabolites') as possible for use on different biological targets, particularly in oncology. The net results did not meet expectations, and Ziconotide (2004), isolated from the toxic sea snail Conus magnus, entered the analgesic market only28 years after Vidarabine. Although toxic microalgal blooms (for example 'red tides') represent true public health issues, marine bio-toxins are also attracting significant attention for the new drug potential they represent. After 21 years of research, the Pharmamar company successfully put its first cancer drug (Trabectedine, from the sea squirt Ecteinascidia turbinata), on the market (Fig. 1). In 2010, eribulin mesylate, a molecule developed from a substance produced by a sponge, also entered the anti-cancer market (Fig. 2). Several other molecules are still in late-stage clinical trials, and may soon be added to the marine pharmacopoeia. Production methods mainly use chemical synthesis, or more recently biological synthesis, and these two methods offer few wealth development perspectives for the countries where these molecular treasures are found.

Fig. 2 – **The marine ecosystem of the Caribbean, where sponges dominate in biomass and diversity: a reservoir of exploitable molecules.** © T. PÉREZ. ■

Towards an sustainable approach

Bioprospecting is still ongoing in little-known zones of the oceans, especially near to the poles or in the deep sea. However, local resources have probably been underestimated, one reason being the high-throughput screening, which aims to determine the pharmacological potential of marine biomolecules as quickly as possible. Indeed, this race for the miracle molecule is often undertaken to the detriment of in-depth study of marine biodiversity and of the mechanisms leading to chemodiversity. So far, the impact on populations in developing countries, particularly in island territories that rely heavily on the sea and its resources, has been negligible. Breaking free at least temporarily from the influence of the pharmaceutical industry, French interdisciplinary research projects, such as ECIMAR in the Mediterranean or CRISP in the Pacific, have helped to reveal even greater chemical diversity. More environmentally friendly, sacrificing much less biomass and inspired by the observations of the natural sciences, the approaches proposed also involve local communities, through training programs and initiatives to raise awareness about their rich marine resources. Such initiatives are organized at national level in Scotland (Aberdeen), Norway (Marbio), Australia (Flinders), Germany (Kiel) and Ireland (Galway), to encourage the emergence of large interdisciplinary structures, bringing together marine chemists, natural scientists and ecologists specialized in marine bio-discoveries. Only this type of association will contribute to the sustainable development of emerging countries, and make possible the virtuous exploitation of this form of ecosystem service.

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8. New technologies in marine ecology

Shawn Hinz, Laurent Chauvaud and Jennifer Coston-Guarini

Over the last few decades, rapid technological progress has helped further our knowledge of the marine environment. These developments, which were previously a military concern, are now an issue for civil society. If we are to study marine environments accurately, data collection needs to cover every scale of time and space, from the micro-layer of the sea's surface to deep-sea environments, and complex geographic areas, especially land-ocean interfaces. The development of sensors and support software is now focused on the integration and processing of data collected by an array of sensors. Progress means increasing miniaturisation and greater data collection and storage capacities.

The developments and applications appear to be infinite but new technologies are only useful if these large data sets can be validated. The technology 'gold rush' is based on the ongoing development of techniques to analyse huge data sets. Marine ecology is thus now squarely placed in the realm of 'Big Data'.

New technologies are inspiring new concepts in ocean sciences as they make it possible to cover organism behaviour and the dynamics of ocean systems in the same study (Fig. 1).

Fig. 1 – **Accelerometers fitted to the upper shells of *Placopecten magellenicus* individuals at a study site in Saint Pierre and Miquelon.** © E. AMICE / CNRS. MATISSE project (L. CHAUVAUD and P. POITEVIN). ■

Laser and acoustics

Laser technology is not entirely new but its recent application to marine ecology systems is of great value. Lasers provide excellent spatial resolution for measurements at every scale. For example, laser-induced breakdown spectroscopy (LIBS) is used to analyse the spectrum of matter in any state (liquid, gas or solid) and, in theory, detect all the elements, the only limit being the power of the laser. Meanwhile, advanced laser fluorometry (ALF) measures various parameters of a sample's fluorescence (intensity, spectral wave length...) for greater accuracy. The latest airborne LIDAR (remote sensing technology) systems detect diverse molecules and are especially useful in characterizing organic compounds. Laser scanning instruments produce detailed topographic and structural representations of habitats for behavioural studies. Finally, real-time 3D laser imaging systems have been developed to study organism behaviour.

In the field of acoustics, our capacity to analyse 'sounds' has improved considerably. Interferometric and mono/multi-beam sonar now have greater resolution and reduced distortion levels. New systems are emerging, such as the sonar able to create a 3D image of underwater objects, 3D multibeam sonar able to work in turbid environments, passive hydrophones used to identify the origin of uni- or omnidirectional sounds and detect ultrasounds to track marine organisms, and finally acoustic telemetry to monitor aquatic animals.

Unmanned vehicles

The arrival of small remotely-operated vehicles (ROV) and autonomous underwater vehicles (AUV) has considerably extended researchers' ocean exploration range (cf. III.8). These vehicles are constantly improving and provide virtually continuous measurements, operating at depths of less than 1 metre, in difficult conditions and enabling personalised configurations that can be modified on-the-go. New systems use scanners to circumvent obstacles and have powerful vertical propellers so they can be used in complex environments.

Aerial drones are also increasingly used for ocean sciences, with some surprising applications. Aerial photogrammetry, for example, has helped scientists to monitor the health condition of killer whales and provide an accurate estimate of births and mortality. This technology is also used to monitor coastal erosion, map algae and seagrass beds (Fig. 2) and analyse whale breath.

Finally, vehicles and probes may be equipped with 'motion reference units' (MRU) with accelerometers that measure g-forces such as gravity or those caused by changes in the device's movement. They have many diverse applications, *e.g.* compensating the movements of probes, controlling the direction and bearing of vehicles, or measuring waves. Accelerometers are also used to measure biological responses (vibrations, shell movements...).

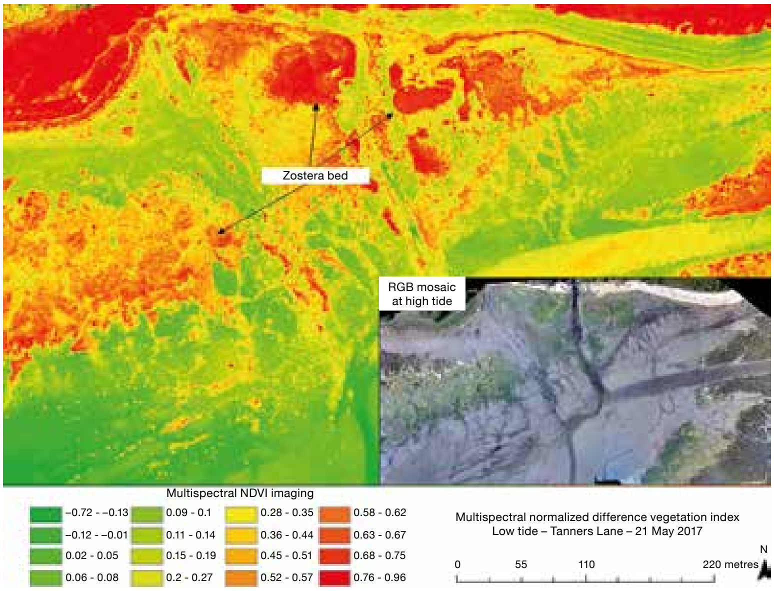

Fig. 2 – **High-resolution multispectral images collected on a seagrass bed using an AUV at low tide.** Source: Gravity Marine Consulting. ■

What is the future for marine technologies?

New sensor technologies will continue to develop rapidly. Advances with consumer electronics also drive progress in marine technologies. As they become more accessible, they enable measurements at a finer scale and increase the range of biotic and abiotic parameters that distinguish an ecosystem. Nonetheless, the increase in data collection capacity is faster than the ability to analyse the data; developing new algorithms is thus a priority.

The progress made in marine technologies increasingly overlaps with biotechnology. The detection of environmental DNA (eDNA) will change the way biodiversity is studied. *In situ* eDNA detection systems are now available on the market and can be controlled by portable computer platforms. This offers huge potential for the monitoring and detection of pathogens or non-native species.

In this new technological age, sensors created will match the scientific question posed, and their development could go as far as the human mind can imagine, with, however, one limitation, the development of accompanying software that makes possible using these devices efficiently.

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9. The seas and oceans: the ultimate playgrounds of tourism

Olivier Dehoorne

Ever since bathing in the sea first became popular, since people discovered the charms of the seaside and the joys of resorts, we have become ever more enamoured with the ocean. From the 1950s, tourist activities staked their claim on the shores of Europe and North America, then spread around the world, as the various national economies became wealthier and international tourism grew. The global number of visitors to the coasts is difficult to estimate, due to a lack of precise data. Nevertheless, a look at the evolution of international tourism gives us an idea of the scale of this phenomenon: there were 25 million tourists in 1950, 278 million in 1980, 674 million in 2000, and a new world record was set in 2015, with 1186 million tourists. Alongside international tourism, the various national tourist flows total around 4 billion, and the sea is the leading tourist destination for Europeans (63%).

The appeal of the coasts and the call of the ocean

The sea is a vast playground for a wide range of activities. There are three categories of coastal and maritime tourism: aquatic and subaquatic activities (swimming, diving); nautical activities including boating (sailing and yachting), surface water sports (surfing, windsurfing...), traditional activities (canoeing) and new activities (stand-up paddle); and boat excursions and cruises (accommodation, catering and recreational facilities on the same boat).

Sailing and cruising are expanding fast. There are 25 million recreational boats in the world, across 25,000 marinas and leisure ports (source: ICOMIA). There are 448 active cruise liners, and 48 more are being built. These ships welcomed 23.3 million passengers in 2015 (source: CLIA), compared to 16 million in 2011 and barely 100,000 in 1970. The market is still dominated by the North American clientele (52%) and the European clientele (23%), but the Chinese market (4.25%) is growing fast (Fig. 1). The most popular sea for cruises is the Caribbean (33.7% of cruise passengers). This is followed by the Mediterranean (18.7%), then the North and Baltic Seas (11.7%) and the China Sea (9.2%). There are cruises to remote corners of the world, from Alaska to Patagonia, as tourists flock to see sights that may soon vanish, amidst the glaciers condemned by global warming (999,600 cruise passengers in Alaska in 2015).

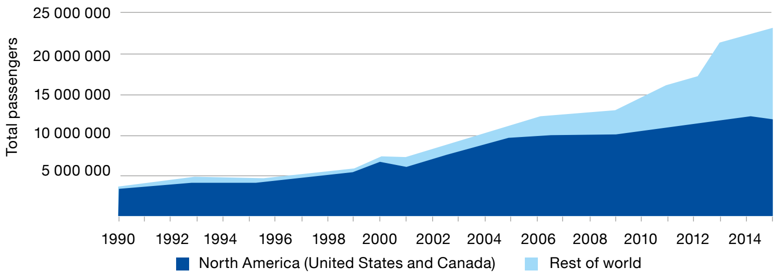

Fig. 1 – **Cruise tourism (1990 – 2015).** Source CLIA. ■

Limitations of the current practices

A whole range of practices are spreading, with flows growing as tourists seek to conquer the ultimate frontiers and try new surf sports, from Australia's Gold Coast to the shores of Bali, from Kuta to Uluwatu. This expansion brings with it unbridled urbanization. Each year, over 10,000 tonnes of suncream end up in the sea water of resorts. These creams contain oxybenzone, which is highly toxic for coral reefs. Underwater diving (scuba and snorkelling) is similarly harmful: hunting, impulsive harvesting, and clumsy kicks from fins all place new pressures on the marine environment.

The growing popularity of the coasts brings with it a process of urbanization, under varying degrees of control. This can be seen on the continental coasts of the Languedoc, the Costa del Sol and the Riviera Maya, or the coasts of islands like the Balearic Islands, Hainan and

Barbados. As our new playgrounds, the coasts are the heart of speculative strategies. Consequently, inflation pushes out traditional activities. New ways of claiming and enclosing areas are sometimes brutal, from Senegal's Petite Côte to the discreet private islands of the Caribbean or the Maldives (for example Mustique or Velaa). The social and environmental dimensions become subordinate to the economic interests of the moment: coastal landscapes are now marked by tourist wastelands (Fig. 2).

The cruise industry raises similar issues, relying on the huge scale of its operations: the average capacity of liners is now 3300 beds, and mega-liners (weighing over 220,000 tonnes) offer 6000 beds. The resultant economies of scale keep production costs low, and allow attractive pricing, in a democratization process synonymous with mass cruises. However, the anticipated economic benefits should be treated with caution: companies have a captive audience, as passengers stay in a floating bubble of safety and fun, against a backdrop of marine and coastal landscapes. Most spending takes place on board. Moreover, the environmental issues are considerable: a ship carrying 3000 passengers produces 800 m^3 of blackwater (toilets), 4000 m^3 of greywater (showers, basins, laundrettes), 90 m^3 of bilge water (oils, lubricants, degreasing agents), 40 tonnes of non-hazardous solid waste (plastic, glass, food waste...) and 2 tonnes of hazardous solid waste. There are significant emissions of atmospheric pollutants (sulphur and nitrogen oxides, and fine particles), because the fuel used is not very refined (and cheaper). These environmental and economic issues explain the recent hostile protests, for example in Venice or Florida (Charleston, Key West...).

Fig. 2 – **Saint Barthélemy, the privacy of a Caribbean island dedicated to luxury tourism, 2015. © O. DEHOORNE.** ■

Towards blue growth

The energy-efficient design of new ships helps to limit the environmental footprint of cruises. They are equipped with the latest exhaust gas treatment and wastewater purification facilities, and the ISO 14001 certified environmental management system was introduced in 2004. Meanwhile, electrical connection points reduce the use of diesel in ports and environment officers ensure compliance with environmental regulations. Environmental performance is also a selling point.

Moreover, certifications and labels identify environmentally responsible players, and help to construct a certain regulation of tourism. The Blue Flag (created in 1985) is present across 49 countries and 4000 sites. Leisure ports with this eco-label have recovery systems for wastewater and special waste, as well as careening areas that do not release waste into the natural environment. This initiative is part of the 'blue growth' strategy for sustainable, intelligent and inclusive growth.

These environmental problems are not unsolvable. Tourists are becoming more seasoned and attentive, and are helping to construct alternative approaches that create a new relationship to the environments and societies visited, and a different attitude to economic situations. The success of ecotourism attests to this. The keys to maritime tourism lie in diversifying ways of exploring and getting close to the sea, oceans and shores, to offer a more intimate connection, on smaller and more environmentally friendly vessels.

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10. SDG 14: an opportunity for small island states?

Anne-France Didier and Fabrice Bernard

The adoption of the Paris climate agreement in 2015 marked a step forward for the human community, hand in hand with the 2030 Agenda and the 17 sustainable development goals (SDG), including SDG 14, 'Conserve and sustainably use the oceans, seas and marine resources for sustainable development' (cf. I.14). The agreement applies to all countries, but specifically recognizes the 57 'small island developing states' (SIDS) identified by the United Nations as regions where the impact of climate change is particularly keen, affecting communities who are among the most vulnerable on the planet and undermining their fragile economies. To deal with the challenges they face, they have formed an international coalition to lend them influence in negotiations. A number of the targets of the 17 SDGs are specific to SIDS, with target 14.7 in particular aiming to ensure that they enjoy the economic benefits of the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture and tourism management.

Vulnerabilities of small island states

Their isolation, their level of endemism (often very high), and the fragility of their ecosystems mean that SIDS are more sensitive than mainland states to biological invasion. This type of disruption has been the primary reason for loss of terrestrial biodiversity over the last 20 years, jeopardizing these islands' food security. Problems are also posed in this regard by the disappearance of tropical rainforests,

Kuna settlement, Robeson Islands, San Blas archipelago, Panama. © Y. ARTHUS-BERTRAND / Altitude. ■

which are critical ecosystems for the balance of the water cycle, the fragmentation of natural coastal habitats such as mangrove swamps and other wetlands, and the loss of rural areas. As a consequence, SIDS are less and less self-sustaining in terms of food and their traditional ways of life are shifting towards intensive agriculture and aquaculture, causing ecosystems to degrade (through malfunction and loss of productivity). The erosion of biodiversity has a direct effect on the islands' inhabitants, who are often highly dependent on natural resources and ecosystem services. The increasing scarcity of healthy ecosystems worsens the already negative impacts of climate change on human societies, which concern access to food and water, and climate-driven migration.

Changes to the coastline also have significant economic and social consequences for SIDS, since beaches and nearby sediments account for a considerable percentage of their exposed, habitable and economically amenable surface area. Not only are small islands geographically remote, they are also less resilient to extreme climate episodes which have a temporary or lasting effect on the environment and communities. Combined with the rise in sea level, these extreme events represent a major threat for the smallest islands and atolls, which often lack both the technical capabilities and the financial resources to take adaptive action.

Towards a sustainable blue economy

With well thought out, committed support from the most developed countries, SIDS could have numerous opportunities for more sustainable development, promoting a sustainable 'blue' economy based on the ocean and its ecosystem services. This approach would dovetail neatly with the international community's objectives for the state and fate of the seas and oceans and their resources. SDG 14 reflects these concerns as follows: *i)* by 2020, sustainably manage and protect marine and coastal ecosystems (...), including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans (14.2); *ii)* by 2030, increase the economic benefits to Small Island Developing States and the least developed countries from the sustainable use of marine resources (14.7), including through sustainable management of fisheries (14.4), aquaculture and tourism, with the prohibition of certain forms of fisheries subsidies which contribute to overfishing and illegal fishing (14.6).

Application in the Mediterranean

In addressing the many structural constraints that they share, the islands' ability to identify innovative initiatives that might be replicated at other territorial scales, including all coastal and nearshore zones, makes them real testbeds for sustainable development. France's Coastal and Lake Shore Conservation Authority (Conservatoire de l'espace littoral et des rivages lacustres, CELRL) recognized this major role as part of the Mediterranean Small Islands (Petites Îles de Méditerranée, PIM) initiative, launched in 2005. This project supports the integrated management of the PIMs by implementing practical measures for sharing knowledge and expertise between the different managers and specialists in the Mediterranean region. The initiative demonstrates the islands' ability to provide tangible, practical solutions to the issues of the integrated management of coastal zones and the sustainable development of micro-territories. Following the initiative's success, in 2014 CELRL began to promote it internationally, creating a network of islands committed to the path of sustainable development, with a designated approach to progress and international recognition. There is in fact a need to consider these often vulnerable and desirable small islands in terms of their diversity and their unique character. The issues raised by SDG 14 can then be reflected locally by means of appropriate local governance rooted in a comprehensive understanding of the ecosystems involved and of societies undergoing change, and incorporating a long-term view.

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11. The future of the Mediterranean Sea

Pierre Chevaldonné and Thierry Pérez

The Mediterranean Sea is a 2.5 million km² link between the Atlantic and the Red Sea, between Europe and Africa, between the East and the West. It has been a concentrated zone of human activities since antiquity including up to our globalized era. This 'miniature ocean' represents only 0.82% of the surface of the ocean, but it's a hotspot of biodiversity, containing 10% of all the marine species of the world, providing a multitude of goods and services to the surrounding human societies.

A transformed relationship between humans and the environment

The relationship between Mediterranean populations and the Mediterranean Sea is ambiguous, but the way they handled the relationship has changed greatly over time. The changes in use are asymmetrical from one shore to the other. Today the massive discharges of macro-waste, wastewater or formerly large quantities of industrial waste from the northern shore are incompatible with the development of our leisure societies and the emergence of environmental awareness. The countries on the southern and eastern shores are facing the massive littoralization of their populations, and their legitimate economic expansion cannot be envisaged without concern for sustainable development. Everywhere new fronts have been opened: highly persistent microplastics or nanopollutants, for example. The artificialization of coastlines and watersheds is unending, the seasonal influx of tourists is increasing, and the primary impact of these phenomena is on shallow marine habitats. An emblematic example of such ecosystems are the Posidonia meadows, once called the 'lungs' of the Mediterranean, and which, as our knowledge progresses, are revealing their services to humankind. These ecosystems protect beaches and dunes from erosion, produce food for the species we consume, and their carbon storage capacity could be among the largest of marine vegetation.

In other times, humans fished for their survival, today they exploit marine resources at industrial scales that quickly reach the carrying capacity of these ecosystems. The population explosion and our use of biological resources are jeopardizing stocks of top predators (such as the Bluefin tuna). These disturbances of trophic equilibria affect the functioning of less resilient ecosystems (such as deep ecosystems), and lead them to new stable states about which nothing is known. Although necessary, the mere exploration of these relatively inaccessible systems to describe the biodiversity and to assess possible ecosystem services is no longer sufficient. One of the major challenges in the Mediterranean is our ability to understand past and present adaptations of some fisheries to regional change, and only interdisciplinary approaches combining fisheries, social, environmental and historical sciences can achieve this objective. In the context of enhancing the cultural and supply services provided by Mediterranean ecosystems through the development of a form of 'marine pastoralism', we need to look at the small-scale traditional fisheries that are deeply rooted in the Mediterranean cultural heritage and that have experienced major disruptions in recent centuries.

Biodiversity in global turmoil

Marine biodiversity is threatened from all sides: splintered habitats fragment populations, reduce connectivity and lead to local extinctions of populations. Globalization also exists under the sea: the introductions of species and invasions are extremely high in the Mediterranean. All the introductory vectors known worldwide operate here, but the main flow comes through the Suez Canal, and these invasions are mechanically favored by global warming. The effects of such invasions on local and natural communities may be irreversible, and in turn, will impact the surrounding

Mediterranean sources of ecosystem services. a) When new fishery resources, such as the crab Callinectes sapidus in Djerba, destroy fishing nets, they are a threat to traditional fisheries. b) Many Mediterranean countries have developed a real underwater tourism industry that greatly depends on the state of conservation of marine ecosystems. c) The carbon sequestration and storage capacities of the Posidonia meadows are exceptional. d) The ecological functions of big erect invertebrates (here the gorgonian Paramuricea clavata) are still not sufficiently understood to fully appreciate the range of services they render to humans. © T. PÉREZ. ■

human populations with a cascade of effects on fishing or tourism for example (jellyfish blooms and the development of new pathogens). Logically, ports are gateways for introductions, reservoirs of non-native species able to colonize neighboring natural environments. To survive transport by boat over thousands of kilometers, a species must be resistant to a multitude of stresses, and successfully settling in a heavily polluted environment requires adaptive capabilities that are largely unknown today.

The distribution of native species, often endemic to the Mediterranean, is being altered at a steady pace. The average ongoing warming of water bodies is accompanied by episodes of increasingly frequent sea-water heatwaves, which push the non-thermophilic species farther north and into deeper waters. The ranges of southern species are increasing steadily, making them excellent bioindicators. Previously absent from the north-west Mediterranean Sea, some species are now a permanent component of catches by regional fisheries (sardinella, barracuda, dolphin fish). This 'good news' does not compensate for the collapse of stocks of small pelagic fish (sprat or anchovy), under the combined effect of the climate, which affects their phenology, and of overfishing. For benthic species attached to the seabed, escaping the heat is impossible. Diseases that in some cases lead to mass mortalities are multiplying in the shallow coastal bottom waters, but the services provided by these recognized components of the Mediterranean natural heritage are not well known. For example, sponges and sea-fans are 'suspension feeders' that filter water, feed on particulate organic matter and play a key role in bentho-pelagic coupling. Some species have been shown to have unprecedented retention and sometimes pollutant degradation capacities. The essential elements of underwater seascapes shape a variety of animals around them, just as terrestrial meadows or forests structure insect or vertebrate assemblages, but the biotic interactions governing the functioning of these ecosystems remain to be discovered. These examples show how little we know about marine support services in the Mediterranean Sea.

Implementing an ecosystem approach is now a priority in the Mediterranean Sea, as is the need to strengthen the interface between politics and science. We must base our naturalist knowledge on current Mediterranean biodiversity. In addition to observation networks of the physical-chemical environment, a whole network of biodiversity inventories, or of observations of biotic interactions within seascapes at the pan-Mediterranean scale need to be set up. The data they produce will better feed predictive models of the possible future of the Mediterranean Sea and its resources.

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12. Future prospects for the Arctic Ocean

Laurent Chauvaud, Philippe Archambault and Vincent Jomelli

The Arctic is the smallest of the world's oceans, spanning a continental and maritime area of almost 21 million km² (approximately 38 times the surface area of mainland France) inside the polar circle. Sea ice seasonally or permanently covers a vast expanse of ocean lying north of the 60th parallel. Climate change induced by the modification of heat flows and radiation in the atmosphere particularly affects this part of the globe which plays a key role in climate balances and has huge cultural, economic and heritage value.

Reduction in ice

Ice is everywhere at the poles and shapes the environment. The ice pack, which covers a very large proportion of the Arctic and Southern oceans in winter, is a refuge for many animal species and the polar bear's preferred hunting ground. In addition, melting ice and snow provide the water and nutrients that plant life requires to thrive in coastal and shore areas.

The 17 million km² covered by glaciers, sea ice and ice caps in the Arctic are subject to close scrutiny because they are highly sensitive to climate change and make a significant contribution to rising sea levels. The 210 marine-terminating glaciers in Greenland retreated by an average 110 metres per year between 2000 and 2010. That retreat was especially evident on the west coast of Greenland, with values sometimes exceeding 1,000 metres a year for the Jakobshavn Isbræ glacier (Fig. 1).

Sea ice has also seen its surface reduced considerably since the 1980s, shrinking by around 30% in summer while its total average thickness has been halved over the past 30 years. The widespread retreat of the ice remains difficult to forecast because natural variability cycles, on a decadal scale, now overlap with the warming of the atmosphere and surface water bodies.

Climate models are used to forecast the future of the cyrosphere in the Arctic zone. They predict the melting of the sea ice glaciers and the polar ice caps over the coming centuries. There are uncertainties as to the speed and extent of the melt, depending on the greenhouse gas emissions scenario applied and the natural variability of the climate and ice caps. Currently, the models predict that the melting of the Greenland ice caps will be slower and will take anything from several centuries to several millennia, but there is still a great deal of uncertainty because some processes that are difficult to simulate could speed up melting (ice flow and marine platform, internal hydrology and lubrication process...).

Modification of ocean circulation

The Arctic Ocean may be seen as a vast semi-closed sea, the topography of which could be described as a 'depression' centred on the pole, with a depth of over 5,000 m.

Coastal circulation is difficult to predict and is considerably modified by environmental changes, especially along the Canadian coasts. For example, the Beaufort Gyre is an anticyclonic ocean current largely conditioned by topography. Atlantic meridional overturning circulation (AMOC) joins the Arctic Ocean from the North Atlantic at the surface to the east of Iceland and along the European coasts. It then cools down, increases in density and moves down to the depths to feed the

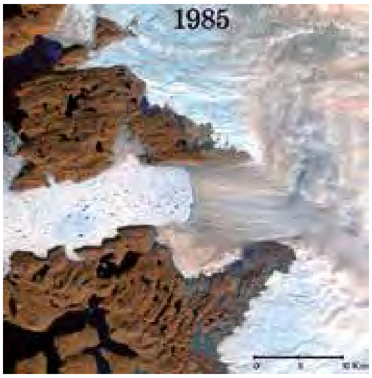

Fig. 1 – **Jakobshavn Isbræ marine-terminating glacier in 1985. © Landsat-EDC / USGS.** ■

Transpolar Drift Stream, reinforced by the sinking of the dense waters of the Laptev and Kara seas.

The mechanisms of heat exchange along the European coasts, often leaving the water free of ice, are important in maintaining thermhaline circulation which conditions climate regimes on a global scale (cf. II.11). AMOC varies over a period of 20 years and tends to become less intense as a result of fresh water run-off.

Fig. 2 – **The East Greenland Current (which originates in the Arctic Ocean) and easterly winds temporarily export icebergs from the north and create another natural source of instability in the Young Sound fjord, which is thus invaded by ice in summer.** © E. AMICE / CNRS. ■

Impacts on the ecosystems

Over the past decade, Arctic marine ecosystems have been particularly affected by the multiple, complex repercussions of the reduction in ice cover, early ice break-up, a local increase in the flow rate of rivers entering the fjords, in turn leading to greater turbidity, and the acidification of water bodies (cf. II.9). These major changes substantially alter the nature and dynamics of primary producers, the basis of the food chains, and have knock-on effects reaching the predators at the top of the trophic pyramids. If consumer and prey activity cycles are desynchronized, there can be a reduction in the energy reserves built up by organisms, with negative repercussions on the dynamics of the populations at the base of these networks (reproduction, recruitment, winter survival...). This can spread to the avifauna, ichthyofauna and marine mammal communities. Recent work has demonstrated the increasingly important role of macro-algae, which have colonized the subarctic zones for less than 20 years; their progress towards high latitudes must be monitored. Finally, the acidificationof the oceans negatively affects species – adults and larvae – with calcareous skeletons (molluscs, corals, sponges...).

The Arctic Ocean is not spared the sixth mass extinction event and a growing number of species originally found south of the Arctic Circle have moved and now colonize polar waters. The consequences of these movements on the ecological functioning of communities are yet unknown. 'New' species may surpass Arctic species in number and provoke strong competition for food. They also unsettle the Arctic trophic networks, ultimately going as far as to alter Inuit culture and values. Some food resources have been greatly reduced for many Arctic species and current trends indicate that the species that depend on sea ice for reproduction, rest or food will be the first to be affected as the ice-free, open water season gets longer. In addition, less ice facilitates maritime transport, which in turn increases the impacts from noise and the dispersal potential of invasive species.

In the Arctic Ocean, the changes occurring are drastically affecting ecosystem functioning and may lead to alternative stable states that are difficult to characterize. One of the challenges for research is to be able to predict when the tipping points will be reached, because their consequences will undoubtedly be irreversible. For the entities responsible for natural resources and public policies in the Arctic, it is crucial that the combined effects of stress factors and potential thresholds are determined in order to prepare appropriately for an uncertain future in this ocean in turmoil.

Article written with assistance from:
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- PART NINE -

Annexes

Previous page:

Hermit crab (*Pagurus prideaux*i), a crustacean found in the Mediterranean and along the English Channel and Atlantic coasts.
© Ifremer / O. DUGORNAY. ■

Glossary

ABIOTIC FACTORS. The physico-chemical factors that influence the organisms in an ecosystem.

ACIDIFICATION. Modification of the natural acid-base state of water by the input of acids, mainly related to the accumulation of CO_2 in OMZs (oxygen minimum zones), which are also one of the most important reserves of inorganic carbon near the surface. Planktonic calcifying species are highly sensitive to this change.

ADENINE. One of the four constituent nucleobases of the nucleic acids, DNA and RNA.

ADVECTION. Transfer of a quantity by the movement of the surrounding environment.

AEROBIC/ANAEROBIC. Descriptions of biogeochemical and biological processes which require (or do not require) the presence of gaseous oxygen or oxygen dissolved in the water.

ALBEDO. Ratio of the solar radiation reflected by a surface to the radiation incident on the surface.

ALGAL BLOOM. Rapid increase in the concentration of a (or several) species of phytoplankton, following natural or anthropogenic changes in the environment. This increased concentration generally leads to colouration of the water (red, brown-yellow or green) and pathological phenomena.

ALTIMETRY. Radar measurement of the distance between the satellite and the surface of the sea.

AMINO ACIDS. The building blocks of proteins. There are 21 different amino acids.

AMNIOTES. A clade of tetrapod vertebrates with an amniotic sac in which the embryo develops. They include sauropsids (reptiles and birds) and mammals.

ANOXIA. Total oxygen depletion in an environment.

APICAL SPECIES. Predator species at the top of the trophic chain (food chain).

ARCHAEANS (ou ARCHEOBACTERIA). Single-cell microorganisms with no nucleus or organelles.

ARTHROPOD. Animal with a segmented body and jointed appendages, surrounded by an exoskeleton (insects, crustaceans, millipedes, spiders, scorpions, acari...).

ARTIFICIAL MARITIME PUBLIC DOMAIN. An artificial MPD is composed of port equipment and facilities, as well as works and installations for the safety and facilitation of marine navigation.

ARTIFICIALIZATION. Transformation of an environment involving a loss of its natural properties, such as its biodiversity, natural cycles (water, nitrogen, carbon, oxygen), biogeochemistry, or physical characteristics.

ATP. Adenosine triphosphate. In all living organisms, this molecule stores the chemical energy that is released in the cell through biochemical reactions.

BAINE CURRENT (and EDDYING CURRENT). Breaking waves lead to an accumulation of water on the coast. This is offset by a baine current or eddying current (rip current) which takes the water back out to sea, following the seabed.

BALLAST (Tanks). The ballast tanks of boats are filled with seawater according to the load carried, to provide weight and stability.

BASAL SPECIES. Species at the bottom of the trophic chain (food chain).

BATHYMETRY. Science studying the relief and depth of the oceans. It aims to map the seabed.

BBNJ (*Biodiversity Beyond National Juridiction*). Conservation and sustainable management of marine biodiversity in zones beyond national jurisdiction.

BEACH SEINE. Drag net used from a beach, which requires large teams.

BENTHIC. Describes organisms living on or near the seabed.

BIOGENIC. Describes an element (organic molecule or mineral) produced or brought about by living organisms.

BIOGEOGRAPHIC PROVINCE. Large spatial unit characterized by cohesive assemblies of species over evolutionary periods, and often associated with particular abiotic or geomorphological characteristics.

BIOLOGICAL CARBON PUMP. All of the biological processes that transform atmospheric CO_2 into organic carbon, via photosynthesis.

BIOMARKER. Measurable biological parameter or marker used as an indicator of a process.

BIOTIC FACTORS. The living organism interactions that influence the organisms in ecosystem.

BLACK SMOKERS. High-temperature hydrothermal vents (up to 400°C), which are acidic, anoxic and loaded with sulphur and dissolved metallic elements. They were made famous by the discovery of the abundant life around them.

BLUE CARBON. Carbon sequestered in marine and coastal spaces (especially mangroves, coral reefs and seagrasses).

BLUE ECONOMY. Set of measures for the sustainable exploitation of marine and coastal resources (text adopted by the French parliament in June 2016). *Blue economy* refers to all the activities connected with the sea. Its regular measurement in terms of gross added value allows us to estimate growth, i.e. doubling by 2030 according to the OECD (2016).

BLUE INFRASTRUCTURE. Generally refers to the ecological and landscape network composed of watercourses and wetlands. In France, the marine blue infrastructure includes the coasts and extends to the marine and undersea areas.

BOSSIS (BUND). Large embankment of earth around salt works, which can be planted.

BULK MATERIALS. In the industrial era, these were raw materials like carbon, minerals, phosphates and oleaginous materials, in large volumes but of low value. They came before high-value colonial products in more limited quantities during the 18th century.

CARBON EXPORT. Flow of carbon leaving the surface of the ocean, mainly in the form of detritus particles, and which supplies the deep ocean.

CARBON SEQUESTRATION. Process by which carbon dissolved at the surface of the oceans is trapped for long periods in the deep ocean.

CCAMLR. Convention on the Conservation of Antarctic Marine Living Resources.

CHAROPHYTES. Group of freshwater or brackish water green algae, characterized by their rough, mineralized stems.

CHARRAU. Access route to salt works and the sea.

CHEMOAUTOTROPH. Organism capable of CO2 fixation, thanks to the chemical energy released by an electronic exchange reaction between an oxidizing agent and a reducing agent.

CHONDRITES. Formed 4.56 billion years ago, these primitive objects tell us about the diversity of the materials that make up planets. Chondrites take their name from the presence of chondrules: small round grains formed by condensation of the nebula.

CLADE. Group of species all derived from a common ancestor.

CNIDARIA. Group of relatively simple animals, specific to the aquatic environment, particularly including sea anemones, jellyfish and corals.

COASTAL EROSION. A set of coastal processes that modify the relief by removing solid matter.

COASTLINE. Virtual line separating land and sea.

COBIER (SALTERN BASIN). Reserve of seawater located between the mudflat and the salt works itself.

COCCOLITHOPHORIDS. Micro-algae measuring 5 to 50 μm, characterized by their calcium carbonate exoskeleton made up of small spherical elements (coccoliths).

COENZYME. Non-protein compound which assists and is indispensable for the correct operation of an enzyme.

COLEOCHAETALES. Group of tiny green multicellular algae living in fresh water or on damp surfaces. They form the 'green dust' that covers damp tree trunks.

CONNECTIVITY. In the theory of graphs and complexity sciences, the capacity of a system, network or node to be connected.

CORAL BLEACHING. Phenomenon of coral die-back, with discolouration following the expulsion of the symbiotic algae (zooxanthellae) that provide pigmentation. This process can lead to the death of the coral.

CORIOLIS FORCE. Effect of the Earth's rotation on all the bodies moving on its surface, which is stronger at the poles than at the equator. It leads to the deviation of currents towards the right of the displacement movement in the Northern Hemisphere and towards the left in the Southern Hemisphere.

CURRENT METER. Device used to measure the speed and direction of the currents. The simplest consist of a small propeller turned by the current, connected to a memory in a watertight case, which continuously records the parameters characterizing the current.

CYANOBACTERIA. Bacteria which carry out photosynthesis similar to that used by plants, during which water molecules are dissociated and dioxygen produced.

CYTOGENETICS. The study of genetic phenomena at chromosome level.

DEADWEIGHT TONNES. Carrying capacity of a ship, corresponding to the total transportable tonnage of goods, therefore excluding the rest of the hull.

DEPOSIVOROUS. Diet based on organic matter and waste deposited on the seabed.

DETRITAL. Describes ground or rock made up of at least 50% rock debris (referred to as 'terrigenous') or solid elements of living organisms such as bones or shells ('biogenic').

DIAPIR. Structure created when lighter rocks move up through denser rocks.

DIATOMS. Group of single-cell micro-algae (2 µm to 1 mm) presented in all environments and surrounded by a siliceous exoskeleton known as a 'frustule'.

DIFFUSIONMETER (or SCATTEROMETER). Instrument for radar measurement of the wind speed and direction over the surface of the sea.

DILUTION PLUME. Describes the marine zone coming out of the estuary, where the fresh water brought by a river is progressively diluted.

DINOFLAGELLATES. Single cell microalgae, between 3 and 50 microns in size, with 2 flagella.

DNA. Deoxyribonucleic acid. The molecule that carries the genetic material in the chromosomes of every cell, and in many viruses.

ECOLOGICAL ENGINEERING. Set of techniques used to manage environments and their development sustainably. These techniques are based purely on using the natural processes of ecosystems.

ECOLOGICAL RESTORATION. Assisting the regeneration of an ecosystem that has been degraded, damaged or destroyed.

ECOSYSTEM SERVICES. Benefits that humans get from natural ecosystems.

EMBRYOPHYTES. Group of plants that develop from a plant 'embryo' after fertilization. These include mosses, ferns, horsetails, selaginella and all seed and flowering plants.

ENDEMISM. Describes the exclusive natural presence of a biological group in a defined geographical region.

ENDOSYMBIOSIS. A form of symbiosis, mutually beneficial cooperation between two living organisms, where one is inside the other.

EUKARYOTES. Single-cell or multicellular organisms, whose cells have a nucleus.

EUPHOTIC LAYER. Zone extending to around 100 m below the surface, with sufficient light exposure for photosynthesis to occur.

EUTROPHISATION. Excessive growth of phytoplankton, due to an excess of a nutrient such as nitrogen or phosphorus. It leads to the deoxygenation of the environment.

FAO. Food and Agriculture Organization of the United Nations.

FERMENTER. Device for the cultivation of microorganisms in a liquid environment, in large quantities or continuously.

FISH SPEAR. Iron instrument on a 2 to 2.5 m pole, for spearing fish in low waters.

FORAMINIFERA. Protozoa, characterized by their perforated mineral skeleton, known as a 'test'. Planktonic species live at the surface and occupy the first few hundred metres of the ocean. Benthic species live on the ocean floor, in the top centimetres of the sediment.

FREE RADICALS. Unstable chemical molecules which are highly reactive, often formed from oxygen, and which cause significant damage to organisms.

GENETIC MARKER. Gene (or sequence) which is easily detectable thanks to its known place on the genome.

GEOPHYSICAL FLUID (dynamics). Study of the dynamics of stratified and/or rotating fluids. A fast, small-scale dynamic is combined with a slower, large-scale flow, strongly affected by the stratification and rotation of the planet.

GUIVRE (SALTERN CHANNEL). Stream associated with the functioning of the basins.

GULF STREAM. Warm oceanic surface current running from east to west in the North Atlantic.

GYRE. From the Greek for 'rotation', an oceanic gyre is a huge spiral of water formed from multiple marine currents. Gyres are a result of the Coriolis force.

HADEAN. Geological period extending from the start of the formation of the Earth, 4.6 billion years ago, to 3.85 billion years BC. It is the first part of the Precambrian.

HALOCLINE. Zone separating two water masses with a very significant difference in salinity (density of salt) and a rapidly changing gradient.

HEINRICH EVENT. Glacial break-off event which took place in the Arctic during the Last Glacial Maximum (from 25,000 to and 15,000 years BC). Icebergs break off from glaciers, melt, and release the sediments that they contain, as well as fresh water, which slows down thermohaline circulation.

HETEROTROPH. An organism that cannot synthesize the organic components on which it feeds, and therefore depends on those produced by autotrophs. This is the case of all animals.

HEXAPODS. Arthropods with only six legs. This includes all insects and collembola.

HORIZONTAL TRANSFER. Process in which an organism integrates genetic material coming from another organism, without being its descendant.

HYPOXIA. Oxygen deficiency in an environment.

ICHTYOARCHAEOLOGY. Area of archaeology specializing in the study of fish remains.

IMO. International Maritime Organization.

INDUSTRIAL FISHING. Exploitation of fish resources, offshore and over long distances, by ships over 25 m long, generally with a tonnage of over 1000 t.

INFRARED RADIOMETRY. Measurement of electromagnetic radiation, with a wavelength between 0.8 microns and 1 mm.

INLET. Channel connecting a coastal pond and the sea, known as a 'grau' on the Languedoc coast.

INTERNAL TIDE. Underwater waves generated by the tide.

INVASIVE EXOTIC SPECIES. Species from another (generally distant) region of the world, introduced locally by human activities. They can proliferate strongly and cause ecological and/or economic damage.

IPBES. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, open to all members of the United Nations (125 states were members at the end of 2016). Created in April 2012, it aims to improve the connections between knowledge and decision-making concerning biodiversity and ecosystem services.

ISOBATH. Level curve joining points of equal depth below water level.

ISOTOPE ANALYSIS. Chemical analysis allowing the identification of the different isotopes of an atom. The isotopes consist of one, two or several atoms, which have the same atomic number, but different numbers of neutrons.

LADURÉE (SALT HEAP). Pile of salt made by the salt worker at the end of their day's work around the pans.

LAST GLACIAL MAXIMUM. Period of the last ice age during which the extent of the ice was at its maximum (from 25,000 to 15,000 years BC). The global temperature was 4-5°C lower than today, the sea level was 125 m lower, and the concentration of CO_2 was around 170 ppm (parts per million).

LONGLINE. Bottom line composed of a main line which is several hundred metres long, equipped with thousands of branch lines (snoods) ending in hooks.

LONGSHORE DRIFT. Sediment transport along a coast, driven by waves and currents.

LOXODROME. A line crossing all meridians of a sphere at the same angle. It is the trajectory followed by a ship on a constant course.

MARGIN. Underwater zone situated on the edge of continents. Morphologically, it includes the continental shelf, the continental slope and the continental rise, thus providing the transition between the shallow and deep waters.

MARINE CURRENT POWER. Electrical energy produced from underwater turbines, with the blades being moved by the marine currents.

MAXIMUM SUSTAINABLE YIELD. Point beyond which the regeneration capacity of a species is no longer guaranteed.

MESHING. Discretization of a continuous environment, in this case, the ocean. The continuous environment is represented by a finite number of points, in the horizontal and vertical dimensions.

MEIOFAUNA. Small animals, measuring between 20 and 250 µm, which live in the sediments.

METAL (MacroEcological Theory on the Arrangement of Life). Theory allowing us to understand the organization of biodiverisity in the oceans, and the assembly and reorganization of species, communities and ecosystems in the context of past and contemporary climate changes.

META-OMICS. Omics data obtained from environmental samples.

METAMORPHIC REACTIONS. Physical and chemical reactions associated with a change of pressure and temperature conditions.

MICROBIOME. All the genomes of the microorganisms living in a given environment.

MICRONEKTON. Includes active-swimming, pelagic animals (mainly fish, molluscs and crustaceans) measuring 1 to 10 cm.

MICROWAVE RADIOMETRY. Measurement of electromagnetic radiation, with a wavelength of 3 mm to 30 cm: between infra-red and radio waves.

MIDDLE PLIOCENE. From 3.3 to 3 million years BC. It is believed that temperature conditions in the period were very close to those predicted for the late 21st century. The global temperature was 2-3°C higher than it is today, for an atmospheric CO_2 concentration close to that currently observed at Mauna Loa. Extra-tropical temperatures were 15°C higher and the sea level 25 m higher than today.

MOLECULAR CLOCK. Comparison of the mutation rate in a sequence of nucleic acids (DNA) from a species that it supposed to have a regular production rhythm, with that of the closest species, in order to deduce how long ago they diverged.

MONOPHYLETIC GROUP. An ancestor and all its current and fossil descendants, without exception.

MSFD. Marine Strategy Framework Directive (2008), aiming to reduce the impacts of activities on the marine environment, in order to maintain and restore its 'good environmental status' by 2020 at the latest.

MULON. Stock de sel temporaire de toute une saline*.

MYRIAPODES. Temporary stockpile of salt from a whole saltworks.

NATURA 2000. Network of natural land and sea sites, selected for the rareness or fragility of their wild flora and fauna species and natural environments.

NEMO (*Nucleus for European Modelling of the Ocean*). Ocean model developed by a European consortium. The NEMO platform calculates the state and evolution of the ocean in three dimensions, from both a physical perspective (marine currents, temperature and salinity) and a biogeochemical perspective (tracers and nutrients), as well as sea ice.

NETRIC. Describes the submerged zone above the continental shelf.

NOROVIRUS. Major cause of acute gastroenteritis among humans of all ages.

NORTH ATLANTIC OSCILLATION. Phenomenon in the climate system of the North Atlantic Ocean, affecting storm tracks towards Europe. It is measured as the atmospheric pressure difference between the Azores high and the Icelandic low.

NUCLEIC ACID. Molecular chain composed of nucleobases (nitrogenous bases), represented by the letters A (adenine), T (thymine), U (uracil), G (guanine) and C (cytosine). The two nucleic acids are DNA and RNA.

NUCLEOBASE (or NITROGENOUS BASE). Cyclic molecule containing nitrogen. Building block of all nucleic acids.

NUTRICLINE. Ocean layer displaying a high variation in its nutrient content, depending on the depth.

NUTRIENT SALTS. Dissolved mineral salts that provide plants like phytoplankton with the chemical elements they need to grow (carbon, nitrogen, silicon, phosphorus).

OCEANIC RIDGE. (Generally underwater) volcano range, marking divergent tectonic plate boundaries.

OFFSHORE WIND POWER. Technology that transforms the kinetic energy of the wind into mechanical and electrical energy, using turbines.

OLIGOTROPHIC. Describes a zone with a low nutrient concentration.

OMICS. All the data obtained from genomics, transcriptomics, proteomics, metabolomics, etc., using high-frequency technologies.

OMZ (Oxygen Minimum Zones). Underwater zones where the concentrations of O_2 are minimal between 10 and 1000 m deep, located essentially in the Pacific and the North Indian Ocean.

ORBITAL VELOCITY OF WAVES. Speed of water particles following circular (orbital) trajectories as waves pass. The orbital radius decreases exponentially with depth.

OSMOSIS. Movement of water molecules from a freshwater solution to a saline solution, through a semi-permeable membrane.

OSMOTIC POWER. Technology that uses the phenomenon of osmosis between fresh and salt water to generate a pressure difference and turn a turbine.

OSPAR. Oslo and Paris Convention for the Protection of the Marine Environment of the North-East Atlantic (1998).

OTE. Ocean Thermal Energy. Technology that exploits the temperature difference between the surface and deep waters of the oceans, using the same principle as geothermal energy.

OXIDIZING. Capacity of a simple substance, compound or ion to receive at least one electron from another chemical species during a redox reaction.

PALEOZOIC. Primary era, from 541 to 252.2 million years BC.

PARTIAL PRESSURE. The contribution of a gas to the total pressure of the mixture.

PELAGIC. Describes organisms living in waters near to the surface, or between the surface and the bottom.

PERMAFROST. Permanently frozen ground.

PHENOLOGY. The study of biological rhythms in nature (flowering, seasonal peak of a species).ximum saisonnier d'une espèce).

PHOTIC ZONE. Aquatic zone between the surface and the maximum depth of a lake or an ocean, exposed to enough light for photosynthesis to occur.

PHOTOBIOREACTOR. Device allowing the cultivation of photosynthetic microorganisms in a liquid environment.

PHOTOSYNTHESIS. PBiological process of cells containing chlorophyll, which converts sunlight, CO_2, water and nutrients into plant matter and O_2. Alternative process to chemosynthesis.

PHOTOSYNTHETIC AUTOTROPHS. Plants and cyanobacteria that use light energy from the sun to synthesize their own organic matter from mineral elements, dissolved nutrient salts and trace elements.

PHYLOGENETICS. History of the genetic relationships between living organisms, expressed in the form of a 'phylogenetic tree', where each node or point of connection represents a real or hypothetical common ancestor.

PHYTOPLANKTON. Microscopic algae living suspended in the water and carried along by currents.

PNEUMATOPHORE. Vertical outgrowth of a secondary root, developed on a horizontal primary root of a tree such as the mangrove tree. It allows continuous respiratory gas exchanges in plants that are alternately submerged (high tide) and out of the water (low tide).

POCKMARKS. Depressions on the seabed, caused by fluids (gases and/or liquids) coming up from the substrate (rock/sediment) to form a cold or hot eruption and re-mobilize the sediment by the current passing through it.

POLYMETALLIC NODULES. Concretions measuring centimetres to decimetres, made up of concentric layers of iron and manganese hydroxides, as well as rare metals, around a core. Present today in the deep oceans at depths of 4000 to 5000 m, primarily in the Indian and Pacific oceans.

PORTOLAN CHART. Name given by 19th-century historians to a type of marine map drawn on parchment and often illuminated.

POTENTIAL ENERGY. Energy involving forces, and which has the potential to become another form of energy. In the ocean, the main force involved is gravity.

PRECAMBRIAN. The longest period of time in the history of the Earth, starting 4.6 billion years ago and ending 541 million years ago, at the start of the Paleozoic.

PRIMARY PRODUCTION. Quantity of organic matter produced through photosynthesis, by autotrophic organisms (primary producers).

PROPAGULES. All or part of an organism allowing the reproductive cycle to be completed.

PROTOSOLAR NEBULA. The planets were created by the aggregation of small bodies forming a homogeneous disc, a nebula, gravitating around a primitive sun.

PROTOZOA. Mobile, single-cell eukaryotes which ingest their food through phagocytosis.

PROXY. Indicator based on geochemical or micro-palaeontological methods, allowing the reconstruction of a physical quantity such as temperature.

PURSE SEINE. Net for catching small pelagic fish, used to encircle schools of fish which are attracted using an electric light. Its lower part, which has a series of rings, closes thanks to a sliding cable pulled from the ship. Introduced for the first time in Italy, in 1925.

QUICKWORKS. The part of a boat's hull submerged beneath the waterline.

RADIOCARBON DATING. Absolute dating method used in archaeology, based on measuring the radiological activity of the carbon-14 found in all organic matter, including the wood of shipwrecks.

RADIOLARIAN. Single-cell organism measuring 50 to 300 µm, part of zooplankton and most often characterized by a siliceous skeleton.

RARE-EARTH ELEMENTS. Group of 17 metallic elements: scandium, yttrium and the 15 lanthanides. These mineral substances sharing similar characteristics are used in the manufacture of high-tech products.

RCP (*Representative Concentration Pathway*). Scenarios relating to the evolution of the greenhouse gas concentration over this century, set up by the Intergovernmental Panel on Climate Change (IPCC).

REEF FLAT. Shoreward space extending out to sea from the foot of the beach to the reef crest. A transit zone for sediments brought by the waves.

REGIME SHIFT. Large, abrupt and persistent change in the structure and operation of an ecosystem.

RESILIENCE. In ecology and biology, capacity of an ecosystem, species or individual to return to normal function or development after suffering a disturbance.

REVELLE FACTOR. This factor quantifies the change in CO_2 in relation to the change in dissolved organic carbon (DIC): it is a measurement of the 'resistance' to absorption/dissolution of atmospheric CO_2 in the mixed surface layer. Of a value of around 8-13, it primarily varies with the temperature and DIC content.

RHUMB LINES. Lines in a star formation, characteristic of old marine maps, indicating the 32 compass points. The rhumb is the 11.25° angle between two lines.

RNA. Ribonucleic acid. Close relative of DNA, which is thought to have formed before DNA in the history of biological evolution. It is found in all living cells and numerous viruses.

SALT PAN. Compartment assigned to the crystallization and consequent collection of salt. A row of pans ('oeillets') is a 'scanne'.

SALT WORKS (or SALTERN). System of basins, trenches and channels, beyond just the crystallization areas where salt is collected.

SALT WORKER (PALUDIER). Worker who develops and harvests the salt belonging to the landowner.

SALT MARSH. Natural flatland with low vegetation, located near the sea, which is flooded with salt water at high tide only.

SAR. Synthetic Aperture Radar.

SARDINE NET. Drift net used to catch small pelagic fish (sardines, anchovies), which appeared at the end of the 15th century in the Gulf of Marseilles.

SEA GRABBING. The modification of rights of access to exploit the marine space or marine resources can lead to local communities being dispossessed of their traditional rights.

SHIFT. At sea, each 24 hour period is divided into three lots of eight hours, worked by three different groups of people.

SHIPPING ALLIANCES. Arrangements between shipping companies allowing them to share the transport capacity of their vessel fleets, in order to save money and avoid the 'empty return' of containers on certain routes.

SLOW STEAMING. Reducing the speed of ships to save fuel, while offsetting this with increased cargo capacity.

SPIRACLE. Opening on top of the heads of primitive vertebrates, and by analogy, on the abdomen of arthropods, allowing (generally aerial) respiration.

SPORANGIA. Plant structure containing the spores used for sexual reproduction in embryophytes.

STENOHALINE. Describes a species which cannot tolerate large variations in salinity.

STREAMING. Current caused by the swell in the bottom boundary layer, directed towards the coast.

STREPTOPHYTES. Group of plants including the charophytes, the coleochaetales and all the embryophytes.

SUBDUCTION ZONE. Zone where the oceanic lithosphere descends beneath another oceanic or continental lithosphere, and disappears, sinking down into the earth's mantle.

SUBSTRATE. Material that provides the surface on which something is deposited, such as a volcanic rock on which encrustations are deposited.

SURGE. Temporary elevation of the sea level due to swell, the wind or a drop in atmospheric pressure, particularly during a storm.

SWASH. Rush of water up and down a beach following a breaking wave. The furthest point reached by the swash defines the effect of storm surges.

SWATH ALTIMETRY. Unlike conventional altimetric radars, which provide measurements vertically from the satellite, the future swath radars, for example SWOT, will allow measurements to be taken across a swathe, or observation zone, of around 120 km across.

SYMBIOSIS. Relationship and cooperation between two organisms of different species.

TEST. Mineral (calcium carbonate, silica) or chitin shell that protects organisms such as sea urchins.

THERMAL BREEZE. Diurnal wind created by thermal differences on the coast (sea/onshore breeze blowing in the day towards the continent and land/offshore breeze at night towards the sea).

THERMOCLINE. Boundary between the deep, cold waters and the warmer, surface waters.

THERMOHALINE CIRCULATION. Large-scale oceanic circulation caused by density differences in seawater, due to differences in the temperature (thermo) and salinity (haline) of water masses.

TIDAL CREEK. Channel subject to the movements of the tides, which supplies the ponds of the salt works, but also allows coastal vessels to access the salt marshes.

TRÉMET or TESSALIER (SALT PLATFORM). Temporary storage area for salt from a group of pans.

TROPHIC (NETWORK or CHAIN). Also referred to as the food web and food chain. All the interactions relating to food resources between species in an ecosystem.

TUNNY NETTING. Fishery using fixed gear for catching tuna.

TURBIDITY. Suspended matter content (organic matter, mineral matter, organisms) in a fluid, which makes it cloudy, causing it to absorb, diffuse and/or reflect light.

TWENTY-FOOT EQUIVALENT UNIT (TEU). Measurement of container traffic, used to describe different sizes or lengths of boxes handled in a port or transported by a ship, based on the standard of a 20 foot (6.096 m) long container.

UNCLOS. United Nations Convention on the Law of the Sea, signed in 1982 in Montego Bay.

UNEP. United Nations Environment Programme.

UPWELLING. When cold, nutrient-rich water rises and fertilizes the surface layer of the ocean, generally due to strong sea winds parallel to the coast.

VERTICAL SHEAR. Caused by noticeable variations in the speed or direction of currents on the vertical of a water mass.

VIVIPARITY. Development of the embryo in the mother's utero (animal) or in the seed (plant) while the fruit is still on the tree.

WATER COLUMN. Concept used in oceanography, allowing the description of the physical, chemical and biological characteristics of seawater at different depths. It extends from the surface to the seabed.

WAVE POWER. Electrical energy produced from successive waves, which are created by wind on the surface of the sea and sometimes propagated over very long distances.

WFD. European Water Framework Directive (2000) aiming to maintain and restore the state of the surface waters (continental and coastal marine) and groundwater, in a legislative framework which is coherent at European level.

ZOOPLANKTON. Marine animals present at the surface and the sub-surface of the ocean.They are most of the time small size organisms and move according to the currents.

ZOOXANTHELLAE. Single-cell algae, which can live in symbiosis with the coral, but also with clams and many jellyfish species.

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Laboratories and organizations

Académie des technologies. *www.academie-technologies.fr*

AD2M. Adaptation et diversité en milieu marin. CNRS/Université Pierre et Marie Curie. *www.biogenouest.org/unite-de-recherche/mer/adaptation-et-diversite-en-milieu-marin-ad2m*

AFB. Agence Française pour la Biodiversité. *www.afbiodiversite.fr*

AGROSCAMPUS OUEST. Institut national supérieur des sciences agronomiques, agroalimentaires, horticoles et du paysage. Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt/Ministère de l'Éduction nationale, de l'Enseignement supérieur et de la Recherche. *www.agrocampus-ouest.fr*

AMURE. Aménagement des Usages des Ressources et des Espaces marins et littoraux.CNRS-INEE/Ifremer/Université de Bretagne Occidentale/OSU-IUEM. *www.umr-amure.fr*

BOREA. Biologie des Organismes et Ecosystèmes Aquatiques. Muséum national d'Histoire naturelle/Université Pierre et Marie Curie/Sorbonne Universités/Université de Caen Normandie/Université des Antilles/CNRS-INEE/IRD. *http://borea.mnhn.fr*

CEBC. Centre d'Études Biologiques de Chizé. CNRS/Université de La Rochelle. *www.cebc.cnrs.fr*

CEFE. Centre d'Écologie Fonctionnelle et Évolutive. CNRS/Université de Montpellier/Université Paul Valérie Montpellier /École Pratique des Hautes Études/Montpeller SupAgro/INRA/IRD. *www.cefe.cnrs.fr*

CEJEP. Centre d'Études Juridiques et Politiques. FREDD/Université de La Rochelle. *http://cejep.univ-larochelle.fr*

CERHIO. Centre de Recherches Historiques de l'Ouest. CNRS/Université Rennes 2/Université Bretagne Sud/Université du Maine/Université Angers. *www.sites.univ-rennes2.fr/cerhio*

CLORA. Club des Organismes de Recherche Associés. *www.clora.eu*

CNRS. Centre National de la Recherche Scientifique. *www.cnrs.fr*

CNRS-INEE. Institut Écologie et Environnement du CNRS. *www.cnrs.fr/inee*

CNRS-INSU. Institut National des Sciences de l'Univers du CNRS. *www.insu.cnrs.fr*

CRHIA. Centre de Recherches en Histoire Internationale et Atlantique. Université de Nantes/Université de La Rochelle. *www.crhia.fr*

CR2P. Centre de Recherches sur la Paléobiodiversité et les Paléoenvironnements. CNRS/Muséum national d'Histoire naturelle/Université Pierre et Marie Curie. *http://paleo.mnhn.fr*

CRH. Centre de Recherches Historiques. EHESS/CNRS. *http://crh.ehess.fr*

CRIOBE. Centre de Recherches Insulaires et Observatoire de l'Environnement. CNRS/EHESS/Université Perpignan Via Domitia/Paris Sciences et Lettres. *www.criobe.pf*

DRASSM. Département des recherches archéologiques subaquatiques et sous-marines. Ministère de la Culture. *www.culture.gouv.fr/fr/archeosm/archeosom/drasm.htm*

ECOLAB. Laboratoire Écologie Fonctionnelle et Environnement. Université Toulouse III Paul Sabatier/CNRS/INP ENSAT. *www.ecolab.omp.eu*

EM3B. Laboratoire Ecosystèmes Microbiens et Molécules Marines pour les Biotechnolo-

gies. Ifremer.
wwz.ifremer.fr/bacteries_marines

EPOC. Environnements et Paléoenvironnements Océaniques et Continentaux. Université de Bordeaux/CNRS/École Pratique des Hautes Études.
www.epoc.u-bordeaux.fr

ESPACE. Étude des Structures, des Processus d'Adaptation et des Changements de l'Espace. CNRS/Aix-Marseille Université/ Université d'Avignon et des Pays du Vaucluse/ Université Nice Sophia Antipolis.
www.umrespace.org

FED 4124. Fédération de recherche Histoire et archéologie maritimes. Université Paris Sorbonne/Musée national de la Marine/ Ecole navale.
www.mer.paris-sorbonne.fr

GÉOGRAPHIE-CITÉS. CNRS/Université Paris 1 Panthéon-Sorbonne/Université Paris 7 Denis Diderot.
www.parisgeo.cnrs.fr

GÉOSCIENCES RENNES. CNRS/Université de Rennes 1.
https://geosciences.univ-rennes1.fr

IAEA. International Atomic Energy Agency.
www.iaea.org

IBPS. Institut de Biologie Paris Seine. CNRS/Université Pierre et Marie Curie/Inserm.
www.ibps.upmc.fr

IDDRI. Institut du développement durable et des relations internationales.
www.iddri.org

IFREMER. Institut français de recherche pour l'exploitation de la mer.
wwz.ifremer.fr

IHMC. Institut d'histoire moderne et contemporaine. CNRS/ENS/Université Paris 1 Panthéon-Sorbonne.
www.ihmc.ens.fr

IMBE. Institut Méditerranéen de Biodiversité et d'Écologie Marine et Continentale. CNRS/ Université Aix Marseille/IRD/Avignon Université.
www.imbe.fr

IMRCP. Laboratoire des Interactions Moléculaires et Réactivité Chimique et Photochimique. CNRS/ Université Toulouse III – Paul Sabatier.
http://imrcp.ups-tlse.fr

INSTITUT DE GÉOARCHITECTURE. Université de Bretagne Occidentale.
http://geoarchi.univ-brest.fr

IPEV. Institut polaire français Paul-Emile Victor.
www.institut-polaire.fr

IPGP. Institut de Physique du Globle de Paris. CNRS/Université Sorbonne Paris Cité.
www.ipgp.fr

IPHC. Institut Pluridisciplinaire Hubert Curien. CNRS/Université de Strasbourg.
www.iphc.cnrs.fr

IPSL. Institut Pierre Simon Laplace. CNRS/Université Pierre et Marie Curie/CNES/Université de Versailles Saint-Quentin-en-Yvelines/CEA/IRD/ENS/École Polytechnique/Université Paris Diderot/Université Paris-Est Créteil.
www.ipsl.fr

IRD. Institut de Recherche pour le Développement.
www.ird.fr

IRIS. Institut de Recherche Interdisciplinaire sur les enjeux Sociaux. EHESS/CNRS/Inserm/ Université Paris 13.
http://iris.ehess.fr

ISSI. International Space Science Institute.
www.issibern.ch

ISTEP. Institut des Sciences de la Terre de Paris. CNRS/Université Pierre et Marie Curie.
www.istep.upmc.fr

ISYEB. Institut de Systématique, Évolution, Biodiversité. CNRS/MNHN/Université Pierre et Marie Curie/EHESS.
http://isyeb.mnhn.fr

IUEM. Institut Universitaire Européen de la Mer. Université de Bretagne Occidentale/CNRS/IRD.
www-iuem.univ-brest.fr

L-3AS. Laboratoire Adaptation, Adaptabilité des Animaux et des Systèmes. Ifremer.
www.ifremer.fr/mediterannee

LAD. Laboratoire Aléas géologiques et Dynamique sédimentaire. Ifremer.
wwz.ifremer.fr/gm/Activites/Laboratoire-Aleas-geologiques-et-Dynamique-sedimentaire-LAD

LAMOP. Laboratoire de Médiévistique Occidentale de Paris. CNRS/Université Paris 1 Panthéon-Sorbonne.
https://lamop.univ-paris1.fr

LATTS. Laboratoire Techniques, Territoires et Sociétés, Ponts ParisTech/CNRS/Université Paris-

Est Marne-la-Vallée.
http://latts.cnrs.fr

LBV. Laboratoire de Biologie du Développement de Villefranche-sur-Mer. CNRS/Université Pierre et Marie Curie.
http://biodev.obs-vlfr.fr

LECOB. Laboratoire d'Eco-géochimie des Environnements Benthiques. CNRS/Université Pierre et Marie Curie.
http://lecob.obs-banyuls.fr

LEEISA. Laboratoire Ecologie, Environnement, Interactions des systèmes amazoniens. CNRS/UG/Ifremer.
www.guyane.cnrs.fr/spip.php?article2

LEGOS. Laboratoire d'Études en Géophysique et Océanographie Spatiales, CNRS/CNES/IRD/Université Paul Sabatier.
www.legos.obs-mip.fr

LEMAR. Laboratoire des sciences de l'environnement marin. CNRS/IRD/Université de Bretagne Occidentale/IUEM.
www-iuem.univ-brest.fr/LEMAR

LEP. Laboratoire Environnement Profond. Ifremer.
wwz.ifremer.fr/deep

LER. Laboratoire Environnement Ressources. Ifremer.
wwz.ifremer.fr/lermpl

LETG. Littoral –Environnement – Télédétection – Géomatique. CNRS/ EPHE/Université d'Angers/Université de Brest/Université de Caen/Université de Nantes/Université de Rennes 2.
http://letg.cnrs.fr

LGPM. Laboratoire de Génétique et Pathologie des Mollusques Marins. Ifremer.
wwz.ifremer.fr/sg2m/Laboratoire-de-Genetique-et-Pathologie-des-Mollusques-Marins

LIENSs. LIttoral, ENvironment and Societies. CNRS/Université de la Rochelle.
http://lienss.univ-larochelle.fr

LISBP. Laboratoire d'Ingénierie des Systèmes Biologiques et des Procédés, CNRS/INSA/INRA.
www.lisbp.fr/fr/index.html

LMD. Laboratoire de Météorologie Dynamique. CNRS/ENS/École Polytehcnique/Université Pierre et Marie Curie.
www.lmd.jussieu.fr

LOCEAN. Laboratoire d'Océanographie et du Climat : Expérimentations et Approches Numériques. Université Pierre et Marie Curie/CNRS/IRD/MNHN.
www.locean-ipsl.upmc.fr

LOG. Laboratoire d'Océanologie et de Géosciences. CNRS/Université de Lille/Université Littoral Côte d'Opal.
http://log.cnrs.fr

LOMIC. Laboratoire d'Océanographie Microbienne. CNRS/Université Pierre et Marie Curie.
http://lomic.obs-banyuls.fr

LOPS. Laboratoire d'Océanographie Physique et Spatiale. CNRS/Ifremer/IRD/Université de Bretagne Occidentale.
www.umr-lops.fr

LOV. Laboratoire d'Océanographie de Villefranche-sur-Mer. CNRS/ Université Pierre et Marie Curie.
http://lov.obs-vlfr.fr

LSCE. Laboratoire des Sciences du Climat et de l'Environnement. CEA/CNRS/Université de Versailles St-Quentin-en-Yvelines/IPSL.
www.lsce.ipsl.fr

LVMT. Laboratoire Ville Mobilité Transport. IFSTTAR/Université Paris-Est Marne-la-Vallée/École des Ponts ParisTech.
www.lvmt.fr

MARBEC. MARine Biodiversity, Exploitation and Conservation. IRD/Ifremer/Université de Montpellier/CNRS.
www.umr-marbec.fr

MBARI. Monterey Bay Aquarium Research Institute.
www.mbari.org

MEEM. Ministère de l'Environnement, de l'Énergie et de la Mer.
www.developpement-durable.gouv.fr

MIO. Mediterranean Institute of Oceanogrpahy. CNRS/IRD/Université d'Aix-Marseille/Université de Toulon.
www.mio.univ-amu.fr

MISSOURI BOTANICAL GARDEN. Jardin botanique du Missouri.
www.missouribotanicalgarden.org

MNHN. Muséum national d'Histoire naturelle.
www.mnhn.fr

MnM. Muséum national de la Marine.
www.musee-marine.fr

OOV. Observatoire d'Océanographie de Villefranche-sur-Mer. CNRS/ Université Pierre et Marie Curie.
www.obs-vlfr.fr

PALOC. Patrimoine locaux et gouvernance. Muséum national

d'Histoire naturelle/IRD.
www.paloc.fr

SBR. Station Biologique de Roscoff. CNRS/Université Pierre et Marie Curie.
www.sb-roscoff.fr

SDHA. Société Dunkerquoise d'Histoire et d'Archéologie.
http://sdha.fr.gd

SEGEFA. Service d'Étude en Géographie Économique Fondamentale et Appliquée. Université de Liège.
www.segefa.ulg.ac.be

SHOM. Service Hydrographique et Océanographique de la Marine. Ministère de la Défense.
www.shom.fr

TELEMME. Temps, Espaces, Langages, Europe Méridionale – Méditerranée. CNRS/ Aix-Marseille-Université.
http://telemme.mmsh.univ-aix.fr

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