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OCEAN & CLIMATE PLATFORM

SCIENTIFIC FACT SHEETS

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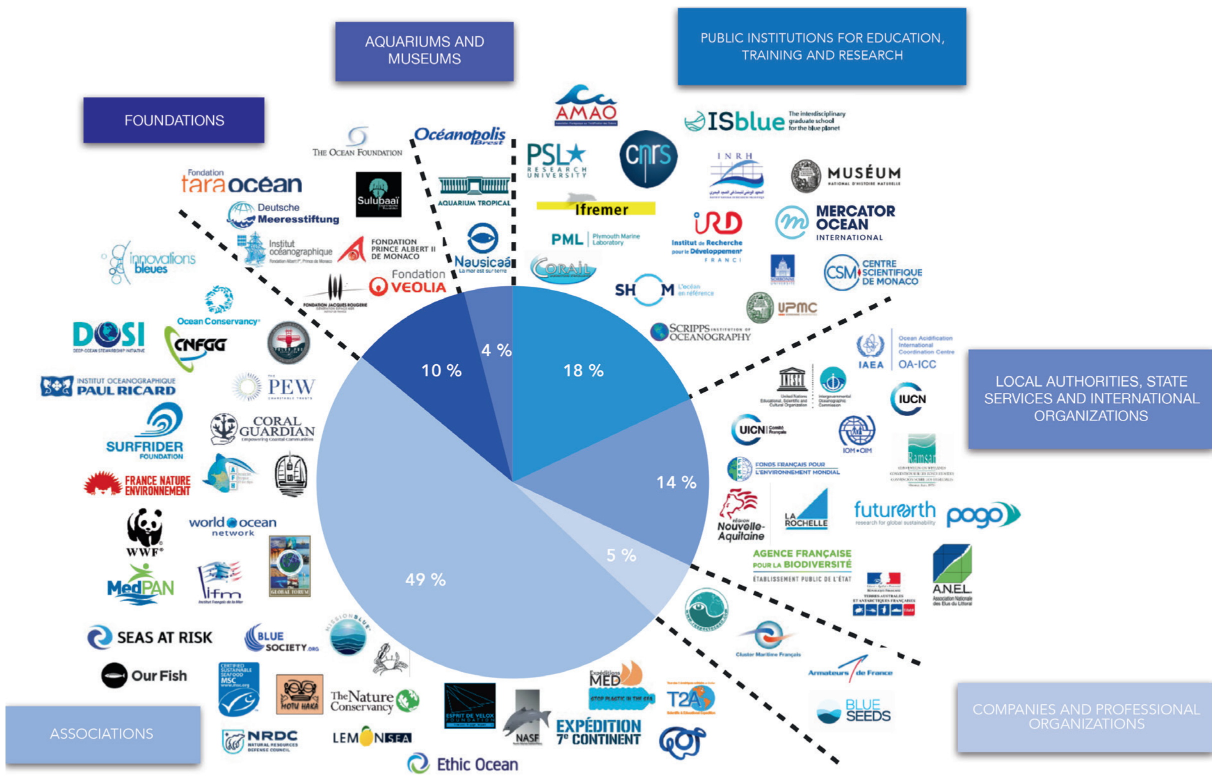
The "Ocean & Climate" Platform

Covering 71% of the Earth's surface, the world ocean is a complex ecosystem that provides services essential to sustaining life on the planet. The ocean absorbs more than 30% of the anthropogenic CO_2 emitted annually into the atmosphere. It is also the world's largest net oxygen supplier, being as important as forests. The ocean is therefore the Earth's main lung and is at the center of the global climate machine.

Even though the ocean continues to limit global warming, human pressure has degraded marine ecosystems over the past few decades, mainly through CO_2 emissions, resource overexploitation and pollution. The ocean's role as a climate regulator is thus disrupted. There is an urgent need to maintain the health of marine ecosystems and to restore those that are deteriorating.

The Ocean & Climate Platform (OCP) was formed out of an alliance between non-governmental organizations and research institutes. It brings together more than 70 organizations, scientific institutions, universities, etc., whose objective is to enhance scientific expertise and advocate on ocean-climate issues with policy makers and the general public.

Relying on its strong expertise, the OCP supports decision makers by providing them with scientific information and guidance to implement public policies. The OCP also responds to a need expressed by both the scientific community and representatives of the private sector and civil society by creating a space dedicated to meetings, exchanges and reflection where ocean and climate stakeholders can build an effective and holistic approach to address the challenges of protecting marine ecosystems and combating climate change.



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Foreword

Françoise Gaill

The ocean is an essential component of our planet's climate. Scientists know this and have proven it time and again: without the ocean, human-induced greenhouse gas emissions would have destabilized the climate machine much more. It is therefore a crucial regulator, but is constantly threatened by human activities and the impacts of global climate change.

The numbers speak for themselves: the ocean covers 71% of the planet's surface, accounts for 97% of its habitable volume, contains 97% of the water on Earth, absorbs 90% of the excess heat and 30% of the anthropogenic CO_2, provides livelihoods for a large part of the world's population, and produces many pharmacological substances. Its ecosystems are worth more than the U.S. GDP! The threats it faces (as well as the communities depending on it) are just as colossal and alarming: acidification, global warming, deoxygenation, rising sea levels, etc.

Yet despite all the stress factors impacting the ocean and its crucial role in climate inertia, international efforts to mitigate and adapt to climate change have neglected it. For more than 20 years, the ocean has not even been mentioned in the additional texts of the United Nations Framework Convention on Climate Change (UNFCCC). Alarmed by this situation, the 70 or so members of the Ocean & Climate Platform (public institutions, NGOs, universities, etc.) have decided to give the ocean a voice during the COP21 climate negotiations.

According to them, the Paris Agreement marked an important step, a major success in taking "ocean and climate" themes into account.

For the first time since the UNFCCC, the Paris Agreement, held in December 2015, explicitly mentioned the ocean in its preamble. In addition, the Intergovernmental Panel on Climate Change (IPCC) published a Special Report entitled "*The Ocean and Cryosphere in a Changing Climate*" in September 2019. It was the first IPCC report on the ocean.

The ocean is now an integral part of the climate negotiations. These achievements are the result of years of advocacy work by the Ocean & Climate Platform and its members.

However, the battle for the ocean does not stop there. It is no longer simply a matter of mobilizing diplomatic processes (which still need to do more to include the ocean); marine civil society must also take part in the Agenda for Action, propose alternatives, set up and support initiatives, disseminate best practices, and share knowledge. The Platform is already part of this process.

First of all, however, we need to gain a better understanding of the ocean. This vast, diverse environment contains unexplored and abundant biodiversity. The ocean floor remains the last terra incognita. Many physical, chemical and biological mechanisms are still unexplained and poorly understood. Scientists and public policy makers must work to fill the knowledge gaps on the ocean-climate relationship. Last year, building on its scientific expertise, the Platform had already published 17 scientific fact sheets. Maintaining its momentum, it now offers you this second volume.

This booklet seeks to be more inclusive and open. Human science is the second fundamental pillar to understand the ocean and the related socio-economic issues. This publication is therefore a mix of "hard" and "soft" sciences, intended to stimulate international reflection on adaptation strategies, persistent gaps and individual behavior, as well as provide a sound basis for understanding human challenges and adapted solutions. We call for a greater integration of "hard" and "soft" sciences.

In order to find solutions to global issues (climate change), research must be interdisciplinary and holistic.

A scientific approach focusing on ocean-climate interactions is currently being developed and faces considerable challenges: collecting sufficiently numerous and diversified data, reducing scales, understanding local and global phenomena, studying surface, intermediate and deep water, from the high seas to the coasts, as well as biodiversity and humans.

The potential for investigation is immense, but absolutely necessary. The ocean is our "comprehensive insurance" and the time is long overdue to protect it!

In keeping with the OCP publications relating to the COP21, this set of articles revisits a number of key aspects of the IPCC Special Report on "The Ocean and Cryosphere in a Changing Climate (September 2019), and includes new data published since the report came out. The present document provides an overview of the latest ocean-climate developments in order to highlight the key challenges of our time and contribute to taking action.

The ocean, a heat reservoir

Sabrina Speich

The ocean's ability to store heat (uptake of 94% of the excess energy resulting from increased atmospheric concentration of greenhouse gases due to human activities) is much more efficient than that of the continents (2%), ice (2%) or the atmosphere (2%) (Figure 1; Bindoff *et al.*, 2007; Rhein *et al.*, 2013; Cheng *et al.*, 2019). It thus has a moderating effect on climate and climate change. However, ocean uptake of the excess heat generated by an increase in atmospheric greenhouse gas concentrations causes marine waters to warm up, which, in turn, affects the ocean's properties, dynamics, volume, and exchanges with the atmosphere (including rainfall cycle and extreme events) and marine ecosystem habitats. For a long time, discussions on climate change did not take the oceans into account, simply because we knew very little about them. However, our ability to understand and anticipate changes in the Earth's climate depends on our detailed knowledge of the oceans and their relationship to the climate.

THE OCEAN: A HEAT RESERVOIR AND WATER SOURCE

Earth is the only known planet where water is present in its three states (liquid, gas and solid) and in particular in liquid form in the ocean. Due to the high heat capacity of water, its radiative properties and phase changes, the ocean is largely responsible for the mildness of our planet's climate and for water inflows to the continents, necessary for developing and sustaining life.

The ocean, which has a very thin layer of salty water, contains more than 96% of the Earth's water, covers 7% of its surface, and acts as a thermostat, warming the atmosphere and exchanging water with it to form clouds and distribute precipitation (rain, snow, etc.) around the world.

It is therefore the key element of the climate system since it mitigates the ongoing changes due to anthropogenic greenhouse gas emissions by absorbing almost all the excess heat (94%: Cheng *et al.*, 2019) and a quarter of the CO_2 emissions (Le Quéré *et al.*, 2018). Without the ocean, the atmospheric warming observed since the early 19th century would be much more intense.

Our planet's climate is governed to a significant extent by the ocean, which is its primary regulator thanks to the ocean's ability to fully absorb any kind of incident radiation on its surface and its continuous radiative, mechanical and gaseous exchanges with the atmosphere. These exchanges and their consequences are at the heart of the climate system.

The ocean receives heat from solar electromagnetic radiation, mainly in tropical regions, but its surface also exchanges extensively with the atmosphere, at all latitudes where it is not covered with ice. The ocean is not static, and marine currents distribute the excess heat received in the tropical regions towards higher latitudes and the ocean depths, especially through high-latitude transfers in areas where surface waters become denser and sink, mainly due to significant heat losses. It also reacts dynamically to changes in climatic conditions (winds, sunlight, etc.). Transfer and redistribution times are highly variable, on timescales ranging from seasons to years in tropical regions, decades in surface layers, and even up to hundreds or thousands of years in deep waters.

The atmosphere and the ocean exchange not only heat, but also water through evaporation and precipitation (rain, snow, etc.). The oceans store 97% (1,338 billion km^3) of the world's total water resources (1,386 billion km^3), while continents only contain 2.4% and the atmosphere less than 0.001% (Gleick, 1996). Water on Earth circulates continuously in a cycle, referred to as the water or hydrological cycle. In simple terms, water enters the atmosphere through evaporation from the ocean surface (which provides 90% of the water) and continents. Water vapor rises, forms clouds, then water falls back to Earth as rain, hail, or snow. Some of the precipitation remains on plant foliage and returns to the atmosphere through evaporation. Some of the precipitation that reaches the ground also evaporates; the remaining water seeps into the ground where it enters water tables or flows downstream, feeding lakes and rivers, which ultimately carry the water to the oceans.

Water is continuously evaporating from the ocean. Rainfall and river runoff compensate for evaporation, but not necessarily in the same areas.

The salt contained in seawater modifies its physical properties, especially its density. Water exchanges with the atmosphere, river runoff and melt water from sea ice or polar ice caps contribute to variations in seawater density, and hence to ocean circulation and vertical transfers in the ocean. Renewal of surface water through ocean circulation and, in particular, water exchanges with the deep ocean also play a significant role in the CO_2 cycle, moving carbon dioxide-enriched surface waters from high latitudes towards the deep ocean.

THE OCEAN IS WARMING UP

The recent warming caused by anthropogenic greenhouse gas emissions affects not only the lower atmospheric layers and continental surface. The fourth and fifth assessment reports of the IPCC Working Group (hereinafter "IPCC AR4 and AR5") highlighted the critical role played by the ocean both in the long-term response of the terrestrial system to global warming and in short-term projections (IPCC, 2013). Changes in heat and freshwater content can influence the predictability of relevant societal information on a decadal timescale. 94% of the global warming associated with human-induced climate change results in ocean warming (Figure 1; Bindoff *et al.*, 2007; Rhein *et al.*, 2013; Cheng *et al.*, 2019). Climate simulations show that global change in ocean heat content becomes the predominant factor in the global thermal balance on a timescale of several months and provides a more reliable indication of the Earth's net radiative forcing than changes in global surface temperature (Palmer *et al.*, 2011; Palmer & McNeall, 2014; von Schuckmann *et al.*, 2016).

The thermal expansion associated with ocean warming accounts for about 30-40% of the observed sea level rise (WCRP Global Sea Level Budget Group, 2018; Church *et al.*, 2011) and is expected to substantially contribute to future projections for the 21st century (Church *et al.*, 2013). The spatial pattern of the change in ocean heat content exerts a strong influence on local sea level changes and remains a key uncertainty in regional projections of sea level rise (*e.g.*, Slangen *et al.*, 2014; Cannaby *et al.*, 2016; Carson *et al.*, 2016). In addition, scientists are beginning to understand the importance of the spatial pattern of ocean heat uptake in relation to climate feedback and climate sensitivity (Rose *et al.*, 2014; Rose & Rayborn, 2016). In fact, this parameter determines the extent of surface warming generated by a given amount of greenhouse gas emissions.

Changes in the global water cycle, such as variations in water availability, droughts and floods, are a major concern as Earth's climate changes. The ocean accounts for 97% of the water stored in all water reservoirs worldwide, and 80% of the Earth's surface freshwater fluxes occur at the ocean-atmosphere interface (Durack, 2015). Ocean waters contain simple salts (*e.g.* Pawlowicz *et al.*, 2016). During the evaporation process, these salts remain in the ocean. As a result, as water passes from the ocean to the atmosphere, and vice versa, salinity anomalies persist and accumulate, providing indications on the variability or changes in the water cycle.

The changes observed in ocean heat and freshwater content are calculated based on available *in situ* measurements of subsurface temperature and salinity. Although the earliest global survey of ocean subsurface temperature dates back to the H.M.S *Challenger* expedition in the late 19th century (Roemmich *et al.*, 2012), it was not until the late 1960s that widespread measurements of ocean temperature were obtained in the first 300-700 m of the water column (Abraham *et al.*, 2013).

Historical observations of the ocean during the second half of the 20th century were highly concentrated in the northern hemisphere, since these measurements were associated predominantly with research vessels and shipping activity, which was particularly significant in these regions. However, it is only since the mid-2000s, with the advent of the Argo International Program's array of free-drifting profiling floats (www.argo.net), that regular and near-global ocean samplings has become available over the first 2,000 m of the water column (Roemmich *et al.*, 2012; Riser *et al.*, 2016). Argo also provides co-located observations of salinity, from which changes in ocean heat and freshwater content can be deduced.

These co-located temperature and salinity observations allow scientists to calculate the density field and its influence on regional sea level variations (Willis *et al.*, 2008), as well as the related changes in ocean flow (Gray & Riser, 2014). They also provide mechanistic insights into the observed changes through water mass analysis (Desbruyères *et al.*, 2016).

The advent of remote sensing in 1978 with the Seasat Earth-orbiting satellite marked the beginning of a new era in global ocean studies. This first remote platform included a radar altimeter to measure satellite height above the ocean surface, a microwave scatterometer to measure wind speed and direction, a microwave radiometer to measure sea surface temperature, and visible and infrared radiometers to identify clouds, land and water features. The usefulness of these remote space platforms for measuring sea surface temperature was demonstrated in the early 1980s (*e.g.* McConaghy, 1980); in the early 1990s, the integrated quantity of sea surface height was established (*e.g.* Le Traon *et al.*, 1998; Ducet *et al.*, 2000), and the first satellite measuring sea surface salinity was launched in November 2009 (the ESA's SMOS satellite measuring soil moisture and ocean salinity). Several other missions were launched shortly thereafter (*e.g.* Berger *et al.*, 2002; Lagerloef *et al.*, 2008; Fore *et al.*, 2016). Satellite observations provide an exceptional, high-resolution view of surface ocean dynamics in terms of temperature, sea levels and surface salinity.

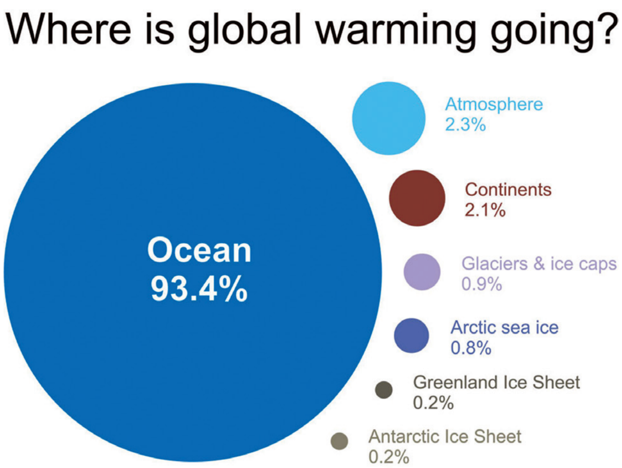


Fig.1 — Visual depiction of the amount of heat associated with anthropogenic global warming that is going into the various components of the climate system for the 1993-2003 period, calculated from IPCC AR4 (Bindoff *et al.*, 2007, section 5.2.2.2.3). This estimate was later confirmed by the IPCC's AR5 (Rhein *et al.*, 2013). Today, the ocean value has been revised upwards: (94% in Cheng *et al.*, 2019). This value is likely be taken up by the IPCC AR6, as well as that of other components of the climate system. It should be noted that focusing on air temperature on the Earth's surface misses more than 90% of the overall warming of the planet. As a result, indexing global warming based on the Earth's surface temperature tends to underestimate this value by 90% (adapted from https://skepticalscience.com/Infographic-on-where-global-warming-is-going.html).

Satellite data ideally complement *in situ* ocean observations by providing a spatial and temporal context for measurements carried out in a scattered fashion by oceanographic vessels and Argo floats. Thus, satellite measurements help solve scale problems or monitor regions that are not adequately sampled or covered by *in situ* observations, as is the case, for example, for variations in coastal oceans and marginal seas associated with river plumes influencing freshwater content at the regional level (*e.g.* Fournier *et al.*, 2016).

In situ measurements are usually much more accurate, ensuring reliable ground conditions to calibrate and validate satellite data. The combined use of these data provides estimates of ocean heat and freshwater content on both global and regional scales (Reynolds *et al.*, 2007; Guinehut *et al.*, 2012; Xie *et al.*, 2014).

OBSERVED CHANGES IN HEAT CONTENT (*I.E.* ENERGY)

Prior to the Argo program, much of the assessment of global ocean variability was limited to annual and seasonal climate cycles (Levitus, 1984, 1986, 1989; Boyer & Levitus, 2002; Kara *et al.*, 2003; de Boyer Montegut *et al.*, 2004), or five-year periods for deep seabeds (Levitus, 1989). Thanks to the Argo international program, much more comprehensive studies on ocean variability during the modern era have been made possible.

Most of the historical measurements took place in the upper ocean layers (0-700 m deep). Our knowledge of long-term change is therefore most robust at these depths (Figure 2; Abraham *et al.*, 2013). Since the first assessments of ocean warming became available, a consistent picture of ocean changes caused by human activities over timescales of several decades has been highlighted through ocean observations (*e.g.*, Levitus *et al.*, 2000). Subsequently, a clearer picture of the ongoing changes has emerged, showing an evident warming of the upper ocean from 1971 to 2010 at an average rate of 107 TW (these estimates range from 74 to 137 TW according to five independent studies), and a weaker warming trend between 1870 and 1971 (Rhein *et al.*, 2013), broadly consistent with our understanding of changes in terrestrial radiative forcing (*e.g.* Myhre *et al.*, 2013).
Even though the measurement coverage area decreased at intermediate depths (700-2,000 m) before Argo, scientists were able to calculate five-year estimates dating back to 1957 (Levitus *et al.*, 2012). These, too, show strong warming over the observed period, but at a slower rate than in the upper ocean. The ocean is therefore accumulating energy at a rate of 4 x 10^{21} Joules per year, equivalent to 127,000 nuclear power plants (with an average production of 1 Gigawatt) discharging their energy directly into the world oceans.

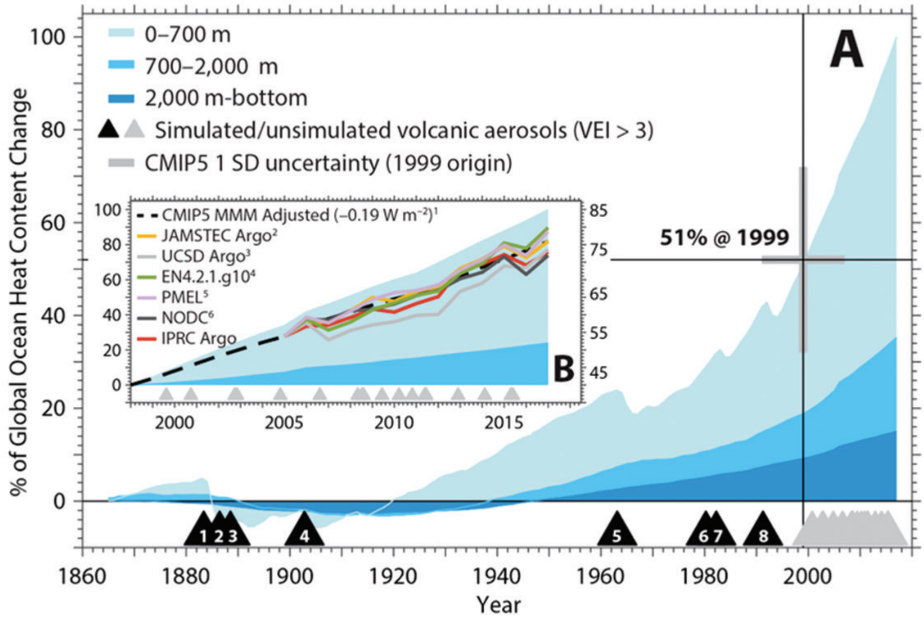
Although all available analyses show a significant historical warming, the patterns and rates differ due to measurement coverage limitations and the different methods used to reconstruct global changes from sparse observations (*e.g.* Boyer *et al.*, 2016; Palmer *et al.*, 2017). This issue has virtually disappeared in the upper and intermediate ocean since the Argo era (Figure 2; Roemmich *et al.*, 2015).

Deep-water measurements (at > 2,000 m in depth) are even rarer than those carried out in the intermediate layer (700-2,000 m deep) and are performed during oceanographic research campaigns using highly accurate and calibrated measuring platforms (GO-SHIP, Sloyan *et al.*, 2019).

Deep-sea layers have also undergone statistically significant warming since the 1990s, with a large regional variability. Seabed monitoring is currently limited to deep hydrographic sections, based on a sparse network of ship tracks that are usually repeated every two to three years, and on moored arrays in the Atlantic Basin (Figure 2; Frajka-Williams *et al.*, 2019).

Deep ocean warming results from downwellings of surface waters between subtropical and polar latitudes. Waters sink down to various depths (200-400 m at subtropical latitudes, 400-1,000 m at subpolar latitudes and down to ocean abysses at polar latitudes), due to heat and freshwater exchanges with the atmosphere that drive the global ocean circulation.

Based on available observations, the deep ocean (below 2,000 m) and the abyssal zone (below 4,000 m) are estimated to have accumulated heat at a rate of 22.3 ± 23.7 TW and 10.7 ± 3.4 TW, respec-



[1]Ridley et al., 2014; [2]Hosoda et al., 2008; [3]Roemmich & Gilson, 2009; [4]Good et al., 2013; [5]Johnson et al., 2018; [6]Levitus et al., 2012

Fig.2 — Ocean models provide us with an overview of how the deep ocean reacts to radiative forcing. When compared with data coverage of the current Argo International Program of profiling floats (www.argo.net) and corrected for the forcing deviations observed since the 2000s, the rate of change in ocean heat content is similar to the observed estimates. Ocean heat uptake (percentage of total 1865–2017 change) for the CMIP5 Multi-model Mean (MMM) layers are presented in the blue wedges for the deep (dark blue), intermediate (blue), and upper (cyan/light blue). The three shaded wedges are combined in the same way as the variation in the global energy inventory performed in IPCC AR5 (Rhein *et al.*, 2013; box 3.1, Fig. 1). The thick vertical gray bar represents 1 Standard Deviation (SD) with respect to the CMIP5 simulations for the year (1999) in which the MMM heat uptake reaches 51% of the net increase (1865-2017) observed during the industrial era, The thick horizontal gray bar indicates 1 SD with respect to the CMIP5 simulations for the year in which the total accumulated heat is 50%. The black (including forcing) and gray (excluding forcing) triangles represent the major volcanic eruptions of the 20th and 21st centuries, the symbol size being proportional to their magnitude. Figure reproduced from Durack *et al.*, 2018 and adapted from Gleckler *et al.*, 2016.

tively, mainly because the Southern Ocean's deep waters have warmed 10 times faster than the North Atlantic's deep basins (Purkey & Johnson 2010; Desbruyères *et al.*, 2016).

CLIMATE CHANGE, OCEAN WARMING AND EARTH'S ENERGY IMBALANCE

The Earth's climate is a solar-powered system. Throughout the year, approximately 30% of the incoming solar radiation is scattered and reflected back into space by clouds and the planet surface. The remaining solar radiation (about 240 W/m²), absorbed in the climate system, is converted into energy (internal heat, potential, latent, kinetic or chemical energy), then moved, stored and sequestered, mainly in the ocean, but also in atmospheric, terrestrial and glacial components of the climate system. Finally, it is sent back into space as outgoing long-wave radiation (OLR: Trenberth & Stepaniak 2003a, b; 2004). In a balanced climate, there is a global balance between the radiation absorbed by the planet and that emitted into space. This balance determines the Earth's radiative balance (Trenberth & Stepaniak, 2003-a, b).

Disruptions to this balance due to internal or external climate changes create a global energy imbalance, causing a radiative flux imbalance at the top of the atmosphere, shaped by several climate forcing factors.

Any variation in the Earth's climate system affecting the incoming or outgoing amount of energy changes the planet's radiative balance and can force temperatures to rise or fall. These destabilizing influences are called climate forcing factors. Natural climate forcing factors include changes in the sun's brightness; Milankovitch cycles (small variations in the shape of the Earth's orbit and its rotation axis that occur over thousands of years), and major volcanic eruptions that inject light-reflecting particles at altitudes as high as the stratosphere. Anthropogenic forcing factors include pollution by particulates (aerosols), which absorb and reflect incoming sunlight; deforestation, which changes the way the surface reflects and absorbs sunlight, and increasing atmospheric concentrations of carbon dioxide and other greenhouse gases, which reduce the amount of heat emitted from Earth into space. A forcing factor can trigger feedbacks that increase (positive feedbacks) or weaken (negative feedbacks) the initial global forcing. Polar ice loss is an example of positive feedback because it makes the poles less reflective. Recent studies show that the Earth is energetically imbalanced – the energy within the climate system is higher than that emitted into space – and this imbalance is increasingly influenced by the atmospheric concentrations of CO_2 and other greenhouse gases. In fact, these gases promote the accumulation of excess heat and cause global warming (Loeb *et al.*, 2009; Hansen *et al.*, 2011; Myhre *et al.*, 2013; Abraham *et al.*, 2013; Trenberth *et al.*, 2014; Allan *et al.*, 2014) (Figure 3).

The most recent studies show that 94% of this positive radiative imbalance causes an (observed) increase in ocean heat content (Abraham *et al.*, 2013; Rhein *et al.*, 2014; Figures 1 and 3a).

A small proportion (a few percent) of this energy contributes to the melting of sea ice and land ice in the Arctic (glaciers, Greenland) and Antarctica. The remaining energy contributes to land and atmosphere warming (Figure 3a), with changes in kinetic and chemical energy making a negligible contribution (Trenberth & Stepaniak, 2003; Trenberth *et al.*, 2002).

Thus, the absolute value of Earth's radiative imbalance is the most important factor defining the state of global climate change and is much more scientifically robust than using the global surface temperature. In fact, it is a measure of the global energy involved in ongoing climate change, whereas the global surface temperature measures only a small fraction of that energy, because the ocean absorbs this surplus of climate energy and retains most of it. Consequently, the best estimate of the Earth's radiative imbalance is the measurement of ocean heat content, supplemented by radiation measurements carried out from space, at the top of the atmosphere (Von Schuckmann *et al.*, 2016).

IMPACTS OF A WARMING OCEAN: SALINITY, FRESHWATER CONTENT AND WATER CYCLE INTENSIFICATION

In parallel with ocean warming, consistent salinity changes have also been observed in both the surface and the lower water layers (Boyer *et al.*, 2005; Hosoda *et al.*, 2009; Durack & Wijffels, 2010; Helm *et al.*, 2010; Mulet *et al.*, 2018). The salinity structure at the ocean surface reflects evaporation and precipitation patterns. Regions with high evaporation rates (such as subtropical atmospheric convergence zones, the Mediterranean Sea and the Red Sea) are characterized by higher salinity concentrations than those receiving high rainfall (such as tropical and subpolar regions). Observations show that salinity differences in these regions are increasing due to an intensification of the land water cycle (Durack *et al.*, 2012; Huntington *et al.*, 2006).

In fact, a warmer climate increases the atmosphere's ability to store water vapor, since this parameter increases with temperature according to the Clausius-Clayperon formula.

The accepted theory is that as atmospheric temperature rises, more water evaporates, mainly over the ocean. As a result, rainfall increases, essentially over land. Moreover, the processes by which clouds and precipitation form in the atmosphere largely depend on the amount, distribution and type of aerosols, because these small atmospheric particles directly influence cloud formation. They can also change the radiation properties of the atmosphere when it is cloud-free. Variations in the water cycle can also be caused by changes in the evaporation properties of soil surface and plants, thus impacting the soil's water storage capacity. If the water cycle intensifies, then all its components are amplified, *i.e.* more evaporation, precipitation and runoff (*e.g.* Williams *et al.*, 2007; Durack *et al.*, 2012; Lago *et al.*, 2016).

Despite this complexity, recent studies suggest that changes in the water cycle are closely linked to an increase in ocean heat content. A warmer ocean provides more heat and water vapor to the atmosphere, thus influencing rainfall patterns worldwide (Held & Soden, 2006; Allan *et al.*, 2010; Smith *et al.*, 2010; Cubash *et al.*, 2013; Rhein *et al.*, 2013).

Salinity analysis as a function of depth also reveals changes (Durack & Wijffels, 2010; Rhein *et al.*, 2013). The most remarkable observation is a systematic increase in salinity contrast between salty subtropical gyres and high-latitude regions, particularly the southern hemisphere. At the scale of the world ocean, contrasts indicate a net freshwater transfer from the tropical regions to high latitudes, showing an intensification of the water cycle.
In the North Atlantic Ocean, the quantitative assessment of heat storage and freshwater inflows over the past 50 years, is consistent with warming that increases the atmospheric water content, leading to an intensification of the water cycle (Durack *et al.*, 2012).

As with the increase in heat content in the deep ocean, salinity anomalies spread throughout the ocean with the global ocean circulation. The most important signal observed is an increase in ocean freshwater content in the Southern Ocean's abyssal and intermediate zones (they have desalinated at a rate equivalent to a freshwater inflow of 73± 26 Gt/year: Purkey & Johnson, 2012; Yao *et al.*, 2017; Silvano *et al.*, 2018), while freshwater content in subtropical and Mediterranean waters is decreasing (Palmer *et al.*, 2019).

The impact of ocean warming on the water cycle induces a feedback affecting climate change. Indeed, water vapor is a greenhouse gas and contributes to accelerating climate warming, and thus water evaporation.

IMPACTS OF A WARMING OCEAN: SEA LEVELS

Current changes in sea levels are the result of various contributing factors caused by changes in the ocean, terrestrial hydrosphere, cryosphere and solid Earth. In fact, changes in the global mean sea level result from ocean thermal expansion (a warmer ocean occupies a larger volume) and changes in ocean mass due to ice mass loss from the Greenland and Antarctica ice sheets, melting glaciers and changes in land water storage (WCRP Global Sea Level Budget Group, 2018). At the regional level, spatial trends in sea levels result from several overlapping phenomena: changes in seawater density are due to changes in temperature and salinity (known as "steric" effects), atmospheric loading, solid Earth deformations and gravitational changes, generated by the mass redistribution associated with land ice melt and changes in land water storage (known as "static" effects; Stammer *et al.*, 2013).

Increased ocean heat is estimated to be responsible for 35-40% of the total sea level rise, estimated at 3 mm/year since satellite measurements became available (Cazenave *et al.*, 2014; 2018).

IMPACTS OF A WARMING OCEAN: OCEAN DYNAMICS AND TRANSPORT

Ocean warming also changes ocean dynamics, as well as heat and salt transport, thus locally disturbing energy exchanges with the atmosphere at its surface.

Global circulation can also be disrupted and affect the climate on a global scale by significantly reducing heat transport to high latitudes and the deep ocean. The IPCC considers it very likely that global circulation will slow down during the 21st century; but not enough to induce cooling in the North Atlantic regions. However, observations made over the past decade do not show a clear trend, but rather strong variations over very different timescales (ranging from weeks to decades: Meinen *et al.*, 2018; Frajka-Williams *et al.*, 2019). However, much longer time series are needed to support any change in ocean circulation. These changes are important, because they also affect changes in the transport of chemical (CO_2, oxygen, nutrients) and biological constituents (planktonic species, fish larvae).

IMPACTS OF A WARMING OCEAN: ICE CAP MELT

Global ocean warming also has a direct impact on the melting of the base of ice shelves and continental glaciers surrounding Greenland and Antarctica, the two main reservoirs of water stored on continents (Jackson *et al.*, 2014; Schmidko *et al.*, 2014; Rignot *et al.*, 2014; Silvano *et al.*, 2018). Thus, while it was already known that global warming was increasing glacier melt, it is now proven that ocean warming significantly contributes to melting the ice shelves extending the Antarctic ice cap over the ocean. For instance, if Antarctica accounts for about 60% of the world's freshwater reserves, studies show that the melting of the base of its ice caps represented 55% of their total mass loss between 2003 and 2008 (Rignot *et al.*, 2014).

ADDITIONAL IMPACTS OF A WARMING OCEAN

Ocean warming also affects the biogeochemical balances of the ocean and its biosphere. While most of these points are noted in the other scientific fast sheets, it can be mentioned that warming is also likely to have an impact on water oxygenation since oxygen solubility decreases as water temperature rises: The warmer the water, the less oxygen it contains. The consequences are marine biodiversity asphyxiation and habitat reduction (Keeling *et al.*, 2010).

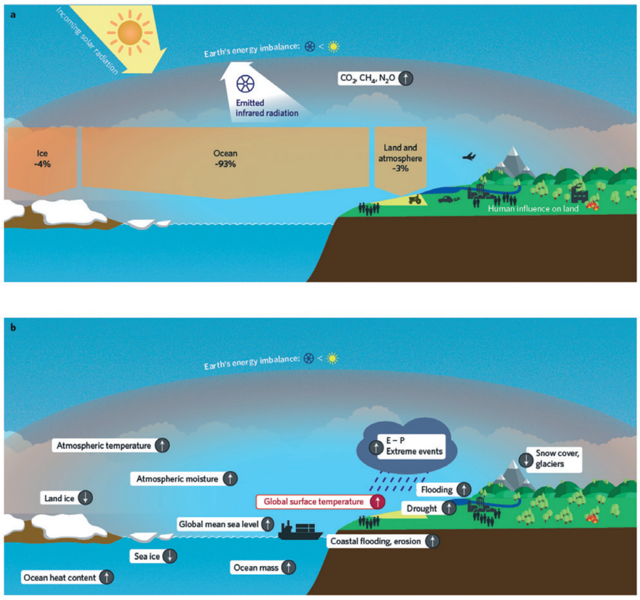


Fig.3 — Schematic representations of energy flow and storage in the Earth's climate system and related consequences. a) Earth's energy imbalance (Earth Energy Imbalance, EEI) resulting from human activities. The world ocean is the main heat reservoir, storing approximately 90% of EEI. The remaining heat warms up the Earth's surface and atmosphere, and melts ice (as indicated). b) The "symptoms" associated with positive EEI, including rises in the Earth's surface temperature, ocean heat content, ocean mass, global mean sea level, atmospheric temperature, and moisture, drought, flooding and erosion, increased extreme events, and evaporation-precipitation (E-P), as well as a decrease in land and sea ice, snow cover and glaciers. Adapted from von Schuckmann *et al.*, 2016.

CONCLUSIONS

Compared with the atmosphere, the ocean has two characteristics that give it an essential role in climate regulation:

1. Its thermal capacity is more than 1,000 times higher than that of the atmosphere, allowing it to store the major part of solar radiation and the excess energy generated by human activities.
2. It has much slower dynamics than the atmosphere and a very high thermal inertia. The ocean is therefore likely to store the disturbances (or anomalies) affecting it over longer timescales, compatible with climate variability.

3. Despite the ocean's slow dynamics, its warming is already affecting the global water cycle, sea levels, polar glacier melt, chemical properties and marine ecosystems (Figure 3b).
4. Recent results suggest that ocean warming has a significant impact on some extreme events, such as tropical cyclones (Trenberth *et al.*, 2018; Emmanuel, 2017; 2018) and potentially affects storm intensity at higher latitudes.
5. The most recent estimates based on observations of the amount of heat accumulated in the ocean in recent decades (*i.e.*, 94% of the excess energy generated by human activities) are in close agreement with the results of numerical simulations of the Earth system (those used in IPCC AR5) over the same period (Cheng *et al.*, 2019). This gives scientists confidence in the results of numerical climate simulations. However, these models predict that if the current trajectory of anthropogenic greenhouse gas emissions (8.5 scenario in IPCC AR5, aka the "worst case" scenario) remains unchanged, the amount of heat stored in the ocean will grow exponentially (Cheng *et al.*, 2019; Figure 4), thus, increasing global warming, extreme events, continental and sea ice melt, and sea levels, as well as drastically affecting marine ecosystems and food availability.

However, we still know very little about the ocean because of its vastness and the technical difficulties inherent in ocean observations (very accurate measurements at pressures exceeding 500 atmospheres, the need for *in situ* measurements aboard vessels involving very high operating costs, long measurement duration and completion times in such a vast ocean, etc.). Moreover, ocean dynamics are very turbulent and interactions with the atmosphere and climate are very complex. Reducing these unknowns and uncertainties is essential to be able to make more reliable predictions about future climate change. Observations and measurements are irreplaceable knowledge sources. There is therefore a need to improve the nature and quantity of ocean observations and to set up a large-scale, long-term observing system, coordinated internationally. This was one of the main objectives set by the international scientific community for the next decade during OceanObs'19, a conference on ocean observations that is held every ten years (http://www.oceanobs19.net; Speich *et al.*, 2019).

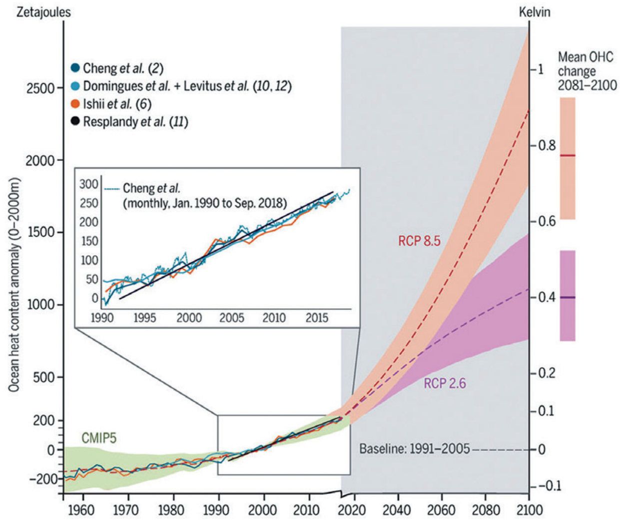


Fig.4 — Past and future changes in ocean heat content. The observed annual changes in heat content are consistent with the different estimates (Cheng *et al.*, 2019; Domingues *et al.*, 2008; Levitus *et al.*, 2012; Ishii *et al.*, 2017; Resplandy *et al.*, 2018) and with the ensemble means of models simulating the Earth's climate system used in IPCC AR5 (defined as CMIP5 models: IPCC, 2013). These results apply to historical simulations prior to 2005 and projections from 2005 to 2017 (supported by recent observations), thus giving confidence in future projections up to 2100 (RCP2.6 and RCP8.5: IPCC, AR5, 2013).

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The ocean, a carbon pump

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The ocean contains 50 times more carbon than the atmosphere and large amounts of carbon are exchanged each year between these two reservoirs. Over the past few decades, the ocean has slowed down the rate of climate change by absorbing nearly 30% of anthropogenic carbon dioxide emissions. While ocean absorption of anthropogenic carbon is the result of physical and chemical processes, marine biology plays a key role in the natural carbon cycle by sequestering large amounts of carbon in deep ocean waters. Changes in these physical, chemical, or biological processes may result in feedbacks to the climate system, thus accelerating or slowing down climate change. These feedbacks between climate, the ocean, and its ecosystems need to be better understood in order to more reliably predict how the ocean characteristics, atmospheric CO_2 and our climate will evolve in the future.

THE OCEAN'S MAJOR ROLE IN THE EVOLUTION OF ATMOSPHERIC CO_2

The carbon cycle involves a wide range of physical, chemical and biological processes, contributing to carbon exchanges between several reservoirs of the Earth system. While the global carbon cycle was roughly balanced before the industrial era began, atmospheric CO_2 has increased by almost 40% over the past 200 years, from less than 0.03% to more than 0.04% of the atmospheric reservoir. This increase is due to emissions generated by fossil fuel burning, cement production, deforestation and other land-use changes. Scientists now consider that such a rapid change is at least ten times faster than any other that has happened during the past 65 million years (Pörtner *et al.*, 2014; Rhein *et al.*, 2014.).

Since the beginning of the industrial period, the ocean has played a key role in mitigating atmospheric CO_2 by absorbing a significant fraction of the anthropogenic CO_2 emitted into the atmosphere. Over the past decade (2008-2017), the world ocean absorbed 2.4 billion tonnes of carbon per year, representing almost 30% of anthropogenic emissions over this period (Le Quéré *et al.*, 2018). Since 1870, the amount of carbon absorbed by the ocean has reached 155 billion tonnes – also 30% of anthropogenic emissions over this period. The ocean thus contributes to slowing down the anthropogenic climate change induced by increased emissions of this greenhouse gas.

A NATURAL OCEAN CARBON CYCLE INVOLVING PHYSICAL/ CHEMICAL AND BIOLOGICAL PROCESSES

Anthropogenic carbon absorbed by the ocean feeds an already considerable natural carbon reservoir. The ocean contains nearly 40,000 billion tonnes of carbon, mainly in the form of inorganic carbon dissolved in seawater. This quantity represents 50 times the size of the atmospheric reservoir. Every year, the ocean naturally exchanges nearly 100 billion tonnes of CO_2 with the atmosphere.

Carbon in the ocean, mainly present in the form of bicarbonate ions (HCO_3^-), is not evenly distributed. Concentrations are higher in deep waters than at the surface, and this uneven distribution of carbon controls atmospheric CO_2 levels. In fact, only the inorganic carbon present in the surface layer is in contact with the atmosphere and contributes to CO_2 exchanges with this reservoir.

This vertical carbon gradient in the ocean is due to both physical/chemical and biological processes.

Biological processes

Phytoplankton lives in the photic zone and uses the sun's energy to photosynthesize. These organisms take up nutrients present in seawater, as well as dissolved inorganic carbon, to produce organic matter. This production is called primary production.

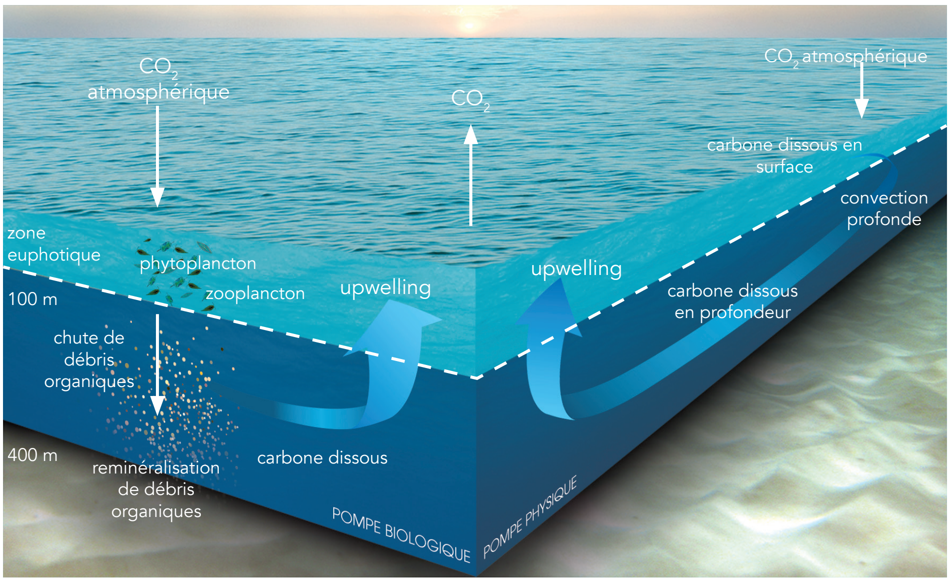
It represents the base of the ocean trophic chains, from which other non-photosynthetic organisms feed. This photosynthetic activity is therefore an effective mechanism for extracting CO_2 from the atmosphere and transferring it to living organisms. Surprisingly, the marine organisms contributing to primary production account for only a small fraction of dissolved carbon (~3 billion tonnes of carbon) in the ocean. However, they are able to generate large quantities of organic carbon each year (almost 50 billion tonnes per year or 50 PgC) to sustain the food chains, thanks to their fast turnover rate, ranging from a few days to a few weeks.

Before being sequestered in deep waters, the atmospheric carbon fixed by photosynthetic organisms undergoes a series of transformations: phytoplankton can be consumed directly by zooplankton, or indirectly by heterotrophic bacteria, which, in turn, will be eaten by larger organisms. In total, only a fraction of the organic matter produced leaves the surface layer as sinking particles (dead cells, detritus, fecal pellets, etc.), thus transferring surface carbon to the deep ocean.

Every year, almost 10 billion tonnes of carbon are thus exported from the surface layer and are responsible for most of the carbon vertical gradient (approximately 90%). All the biological processes contributing to the ocean carbon cycle constitute the biological carbon pump (Figure 1).

Only a tiny fraction (~0.2 PgC/yr) of the carbon exported by biological processes reaches the ocean floor and can be stored in sediments for millennia or even longer (Denman *et al.*, 2007; Ciais *et al.*, 2014); this biological mechanism extracts carbon from the ocean-atmosphere system for very long periods of time.

Over geological timescales, the biological carbon pump has formed oil deposits that are now fueling our economy. Knowing that, every day, large amounts of CO_2 that have been trapped for millions of years are released into the atmosphere (about one million years of trapped carbon is burned each year) makes it easier to understand the current rate of climate change.



Natural carbon cycle and representation of biological and physical pumps (Bopp *et al.*, 2002).

Physical and chemical processes

Physical and chemical processes also contribute to the uneven vertical distribution of carbon. The cooling of surface waters at high latitudes increases their ability to dissolve atmospheric CO_2 (mainly by increasing its solubility) while increasing their density. These waters then sink to great depths, carrying CO_2 away from the atmosphere and thus contributing to the vertical ocean carbon gradient. This is referred to as the physical or solubility pump. Despite the fact that biological processes are responsible for the majority of vertical natural carbon gradient in the ocean, physical and chemical processes nevertheless explain the current anthropogenic carbon sink.

In fact, excess atmospheric CO_2 will lead to a net carbon flux to the ocean, because of the induced imbalance between the atmospheric and ocean concentrations. Anthropogenic CO_2, once dissolved in surface waters, will be transported by marine currents and mixed with subsurface waters.

SATURATION OF THE OCEAN CARBON SINK?

Since the beginning of the industrial era, the ocean has been absorbing an almost constant share of anthropogenic CO2 each year. However, many studies, based on theoretical considerations, and conducted from *in situ* observations, controlled laboratory experiments, or simulated, suggest that several processes may lessen or slow down this natural carbon sink.

The first set of processes is related to carbonate chemistry (exchanges between CO_2, HCO_3^- and CO_3^{2-}) and eventually leads to saturation of the ocean carbon sink. In fact, dissolution of anthropogenic carbon dioxide reduces carbonate content and thus the ocean's buffering capacity, in turn, increasing the proportion of CO_2 in relation to other dissolved inorganic carbon gases and decreasing sink efficiency. This same phenomenon simultaneously causes ocean acidification and could potentially have consequences on ocean ecosystems.

The second set of processes is linked to climate-carbon cycle feedback. This feedback, induced by anthropogenic climate change, affects different carbon absorption mechanisms. Climate change leads to modifications in water temperature, marine currents, and ocean biological production. If these changes increase the carbon sink, in time, they will curb climate change and induce negative feedback.

On the contrary, in the event of decreased carbon sink, the changes will induce positive feedback, accelerating the phenomenon.

Once again, several processes are involved. Water warming, for instance, reduces the ocean carbon sink: a 2 or 3°C rise in surface water temperature decreases CO_2 solubility by a few percent, and thus the ocean's capacity to absorb carbon dioxide. Another effect could further increase carbon sink saturation: in response to rising temperatures, climate models predict an increase in ocean vertical stratification. In other words, vertical mixing, which homogenizes deep and surface waters, is expected to decrease. The resulting stratification will limit the ingress of anthropogenic CO_2 into the deep ocean.

As for the biological pump, its fate is hard to predict. Even a qualitative estimate of the impacts of changes in marine ecosystems on the ocean carbon sink remains highly speculative. Because the functioning of the biological pump is strongly linked to primary production, it is important to consider the impacts of climate change on photosynthetic activity. On continents, CO_2 concentration is generally a limiting factor in photosynthesis. The increase in anthropogenic CO_2 therefore tends to stimulate plant growth (known as the carbon dioxide fertilization effect). This does not appear to be the case in marine systems because of high dissolved inorganic carbon (DIC) concentrations. However, photosynthesis is strongly affected by changes in water temperature, which has increased significantly over the past 150 years. In addition to temperature, light and nutrient limitation (Gonzalez-Taboada & Anadón, 2012; Pörtner *et al.*, 2014) are likely to affect photosynthetic activity, as will oxygen, pH, and salinity.

Models predict an overall reduction in oceanic primary production in response to climate change, though with significant variations depending on latitude. One of the factors leading to this reduction is the predicted expansion of oligotrophic gyres and the decrease in surface nutrient concentrations due to an intensification of ocean stratification. Climate projections, however, show an increase in primary production at high latitudes due to ice melt.

Finally, it is also necessary to assess which types of planktonic species will dominate the ocean ecosystem in response to these changes, since plankton composition can considerably affect CO_2 absorption. The role of some phytoplankton algae, such as diatoms, is particularly significant. Because of their relatively large size compared with phytoplankton cells (ranging from a few tens to a few hundred micrometers), these cells sink quite easily and are therefore responsible for the export of a large fraction of carbon to the deep ocean in productive regions. Nonetheless, diatoms are particularly sensitive to a decrease in mineral salt concentrations. Other phytoplankton cells, abundant in the ocean, but very small in diameter (<10 µm)[1], consume less and could replace them. Due to their size, they are mostly recycled in the surface layer, and thus contribute little to carbon storage in the depths. An imbalance in the diatom/small cell ratio could thus greatly disrupt the biological pump intensity.

Despite these multiple levels of uncertainty — the most important being the biological response to climate change — the different projections produced by numerical models that couple the climate system and the carbon cycle all show a reduction in the ocean sink due to the ongoing warming. Even though this ocean sink is unlikely to become a source, this decrease will affect atmospheric CO_2 concentrations and, ultimately, climate change. By 2100, climate/carbon cycle feedbacks (including the response of the terrestrial biosphere to climate change) could be responsible for an "additional" increase in atmospheric CO_2 concentrations by several tens of ppm2!

The future evolution of the ocean carbon sink, as predicted by models coupling climate-carbon cycle at a global scale, remains very uncertain. The IPCC's latest report points to a number of poorly constrained processes that explain the wide range of uncertainties associated with these projections: these primarily include the living world's response to climate change and changes in the biological pump, but other processes related to the representation of small-scale features (eddies) and to the consideration of particularly complex coastal areas are also mentioned.

MANAGING THE CARBON PUMP TO OFFSET CLIMATE CHANGE

Human activities have disrupted the carbon cycle balance and considerably contributed to changes in the composition of the Earth's atmosphere, just as bacteria, protists and the biosphere in general t have played a role in shaping the Earth's atmosphere in the past.

Like other events that have marked our planet's history in the past, these changes caused by human activities significantly affect the Earth system. Our duty as inhabitants of the planet Earth is now to make the most reliable predictions possible of future changes, react in the best possible way to limit the upcoming disruptions and adapt to inevitable changes.

Studies have suggested that an artificial increase in the ocean carbon pump might improve oceanic carbon sequestration, thus offsetting CO_2-induced climate change. For instance, primary phytoplankton productivity could be stimulated by adding nutrients, such as iron, to waters where this nutrient limits phytoplankton productivity. There is currently no consensus on the effectiveness of these methods, so far limited to a few field experiments. Other geoengineering approaches,

1 1 micrometer (µm) is 0.001 millimeter.

designed to artificially alter the incoming solar radiation by sending particles into the upper atmosphere, for instance, are equally controversial, and cannot solve the problem of ocean acidification.

In conclusion, just as we should protect forest areas on our continents, it is essential to protect the ocean carbon sink. This can only be done by preserving the oceans, marine life and planktonic ecosystems. To better assess the ocean-climate interactions, it is also necessary to better understand the footprint of each component of the carbon cycle, by conducting further fundamental research on the functioning of physical and biological carbon pumps.

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The deep ocean in a changing climate

Nadine Le Bris

The largest inhabited space on the planet is located more than 200 m below the ocean surface, where darkness is almost total. These ocean depths play a major role in mitigating climate change through heat and anthropogenic CO_2 sequestration. In addition to undergoing gradual warming and acidification, deep waters are less well ventilated, which reduces oxygen availability. Changes in surface phytoplankton production also affect the quantity and quality of nutrient resources available in the deep ocean. What will be the consequences of these disturbances on this vast and largely unexplored environment? Models set the framework and predict 50 to 80-year trends, but struggle to provide answers about the near future. Since observations reveal faster changes than model predictions do, there is a pressing need to adapt human activities to address potential risks. Many ecosystem services are linked to exchanges between the seabed and ocean surface ecosystems. These ecosystems play a role in long-term CO_2 and CH_4 sequestration by trapping carbon in the form of carbonates or organic matter (living organisms, debris, particles, or compounds dissolved in water). Increasing temperature, and decreasing oxygen and pH affect species distribution and, more generally, the entire nutrient cycle on which sustainable economic activities, such as artisanal fisheries, are based. Without a better understanding of these phenomena in space and over time, anticipating the consequences of climate change on biodiversity and deep ecosystems remains very difficult, as does assessing the impacts of new industrial activities combining with climate change consequences. Implementing key climate change adaptation measures must be based on an unprecedented effort to acquire the new knowledge needed to establish a legislative framework and effective management tools.

A THERMAL BUFFER FOR THE CLIMATE

Covering nearly two thirds of the planet's surface and representing 98% of the ocean volume, the great depths still appear an inaccessible and marginal zone. Yet the ecological footprint of human activities is rapidly growing, and the deep ocean is now at the heart of major sustainable development challenges. The problems posed by extractive activities, including deep-sea fishing, increasingly deeper oil and gas exploration and exploitation, and deep seabed mining projects, which are by definition "unsustainable", are well known. What is less widely known is that submarine canyons, seamounts and other "animal forests" of sponges and deep-water corals are essential to the survival of some fish species. They also support local fisheries and are an integral part of their sustainability. So-called "ecosystem services" that some seek to quantify economically involve many other functions of these ecosystems. Globally, deep waters and the ocean floor play a predominant role in climate change mitigation, their volume acting as a thermal buffer against climate warming. Almost 30% of anthropogenic CO_2 emissions are stored in the ocean — half of which are sequestered at depths exceeding 400 m, and one quarter below 1,000 m (Gruber *et al.*, 2019). 90% of the heat trapped by greenhouse gases has been absorbed by the ocean — almost half of which is stored at depths exceeding 700 m (42% of the total heat, Abraham *et al.*, 2013).

WHAT CLIMATE MODELS SAY OR DO NOT SAY ABOUT CHANGES IN DEEP WATERS

Climate models describe with increasing precision deep-water warming and acidification, resulting of CO_2 and heat accumulation. They also simulate the transport of organic matter from the surface, where it is produced, to the great depths. In addition, models predict a general decline in organic matter and its progressive consumption by marine fauna and microorganisms during sedimentation (Bopp *et al.*, 2013). According to the atmospheric CO_2 emission scenarios, a decrease in pH, oxygen, and of the quantity of organic nutritive resources exported to deep waters is expected to occur in most deep ocean layers over the next few decades. The rate and magnitude of these changes vary greatly from one ocean region to another. Moreover, they combine with natural variations in seawater conditions with depth, amplifying the decrease in pH, oxygen and organic particulate concentration. Model predictions allow comparing changes among seabed ecosystems and better assess their vulnerability (Mora *et al.*, 2013; Sweetman *et al.*, 2017). These models are even being used to anticipate risks when establishing marine protection areas, such as done for Vulnerable Marine Ecosystems, where FAO limits fishing activities (FAO, 2019).

Factors likely to have a significant impact on biodiversity and the functions it provides depend on the ecosystem type. Scientists gave early warning of the vulnerability of ecosystems relying on deep-water coral colonies (Guinotte, 2006). In the absence of photosynthesis, deep waters are naturally richer in CO_2 and more acidic than surface waters. In many regions, the increase in CO_2 concentrations in the deep ocean, confirmed by long-term series of observation, creates corrosive conditions under which various deep-water coral species should grow their calcareous skeleton made of aragonite. Gehlen *et al.* (2015) predict that most seamount peaks in the North Atlantic Ocean will be affected by this phenomenon. In addition, nutrient-depleted abyssal plains are likely to lose a large share of their macrofauna as a result of increasingly scarce nutrient resources due to changing surface phytoplankton production.

Lastly, oxygen depletion is undoubtedly one of the most significant threats to deep ocean biodiversity and the functions it provides. The situation is particularly critical at intermediate depths (200-700 m), where oxygen concentration is already reduced due to oxygen consumption by microorganisms decomposing organic matter. Oxygen concentration sometimes reaches levels below which all animal life is excluded. These "dead zones", where only microorganisms proliferate, are expanding horizontally and thickening, thereby reducing the habitat of many fish or invertebrate species (Gilly *et al.*, 2013).

These estimates are still very uncertain for many deep-sea regions where measurements are too scarce to calibrate models. Nevertheless, observations confirm that the amount of oxygen in the ocean has decreased by almost 2% per decade since 1960, and low ventilation of deep waters accounts for a large part of the continued decrease in the mean oxygen concentration observed at depths below 1,000 m (Schmidtko *et al.*, 2017). More importantly, oxygen minimum zone expansion exceeds model predictions, and oxygen depletion can reach -4% per decade on the periphery of some of these zones, where critical thresholds are then exceeded (Schmidtko et al., 2017).

As a result, many species' habitats are reduced. For instance, some zooplankton species that migrate from the surface to deep ocean layers during the day and large pelagic fish with high oxygen requirements that dive several hundred meters to feed, are impacted (Stramma *et al.*, 2010, Gilly *et al.*, 2013). Others, such as the Humboldt squid which hunts at the boundary of hypoxic waters (hypoxic zone), benefit from these conditions.

In fact, the physical, chemical, or biological changes occurring at the surface can spread to deeper waters faster than the circulation of large seawater masses on which climate models are based would suggest. Deep ocean ecosystems are closely linked to what is happening at the surface. Particle sedimentation (marine snow), massive deposits of large organisms (salps), daily or seasonal migrations of nekton (free-swimming fish, crustaceans and invertebrates), gyres or downwellings (sinking of surface waters down to the depths under the influence of wind) are all episodic phenomena that directly propagate the disturbances affecting surface ecosystems in the deep ocean.

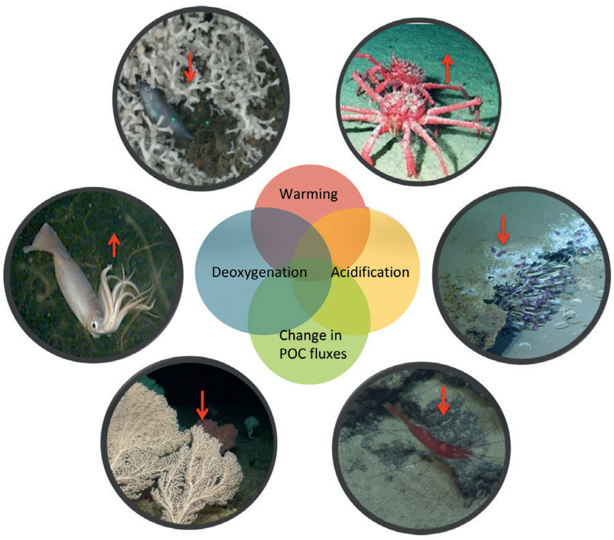

Fig.1 — Deep species exposed to various climate stress factors that are likely to cause major ecological changes. Clockwise: The red king crab is invading the Antarctic Peninsula margin as a result of Atlantic water warming. Fauna living in carbonate crusts in the vicinity of methane seeps, influenced by warming and acidification. Deep-sea shrimps on seamount flanks of the Mediterranean Sea affected by the reduction of organic particle fluxes at depth, gorgonian on the mid-Atlantic ridge exposed to change in organic resource supply and deoxygenation, The Humboldt squid is taking advantage of the decrease in oxygen levels in eastern Pacific mid-depth waters. Cold-water coral is subject to ocean acidification and deoxygenation and is particularly sensitive to water warming in the Mediterranean Sea.
Photo credits: K. Heirman and C. Smith, NSF LARISSA and Ghent University HOLANT projects. C. Pierre & J. Sarazin Ifremer-CNRS, MEDECO cruise 2008, M. Carreiro-Silva & T. Morato, IMAR - University of the Azores, Ocean Azul Fondation). N. Le Bris Ifremer-SU-CNRS CYLICE-ECO cruise 2018. NOAA/MBARI 2006. N. Le Bris, UPMC, Fondation Total, CNRS.

Seabed relief also plays a role in this propagation by locally enhancing vertical mixing of water masses, favoring the upwelling of nutrient-rich deep water, acceleration of currents, and sediment transport to the abyssal zone. The typical kilometer scale of such seafloor features is however lower than the resolution of climate models and they are not accounted. Seamounts, canyons, valleys and faults in oceanic ridges create a mosaic of rocky and sedimentary habitats, in which seafloor biological communities depend on those thriving along the water column. In addition to seabed relief, multiple hydrological structures promote exchanges across various depth ranges, such as fronts, gyres, upwellings, deep convections, and downwellings. All these dynamic interactions are influenced by many climate-related factors, making scientific studies particularly complex when it comes to understanding local interactions and consequences.

So far, detailed bathymetric mapping (*i.e.*, a fine relief description, representative of deep habitats, with a resolution of less than 100 m) has only been conducted on less than 10% of the ocean floor.

WHY WORRY ABOUT DEEP OCEAN CHANGES IN A CONTEXT OF SUSTAINABLE DEVELOPMENT?

The ocean floor and deep waters are already impacted by human activities to varying degrees, from the continental slope to the deepest trenches, due to the accumulation of persistent pollutants and debris, landscape alteration and massive habitat destruction by trawlers, ocean mining disposal and toxic waste dumping. However, these environments are often ignored in discussions on climate change impacts, biodiversity protection, or sustainable development issues. Beyond the regulations imposed on resource exploitation, does the deep ocean deserve special attention? Should its alteration be considered minor because it does not directly deprive humans of habitat or food?

In 1840, researchers declared that life disappeared at depth exceeding 550 m, based on the assumption that marine species cannot survive in the absence of food freshly produced by planktonic micro-algae. This statement was wrong. Since the major expeditions of the late 19th century, deep ocean exploration has revealed a wide variety of dark habitats, which keep growing in number with the advent of robotic exploration and mapping. The ocean floor and deep waters are home to exceptional biodiversity as diverse as the available food sources are, from energy-poor marine snow to chemosynthetic bacteria capable of exploiting chemical compounds issued from the sub-seafloor to grow, whale carcasses or wood falls on the abyssal plains. The inventory of services associated with these ecosystems is just beginning, but the variety of metabolic innovations in deep-sea lineages facing extreme environmental conditions (temperature, acidity, toxicity, corrosive or oxidative stress) constitutes an outstanding heritage (Armstrong *et al.*, 2012; Thurber *et al.*, 2014).

Among the ecosystem services sustained by the deep ocean, carbon dioxide (CO_2) and methane (CH_4) sequestration, nutrient recycling, and the availability of shelter and food for the juveniles of many species are the most cited. The deep ocean is the largest carbon reservoir on Earth. Seabed ecosystems contribute to sequester carbon in several ways, by converting methane and carbon dioxide into carbonate rocks or through deep-sea biomass (Marlow *et al.*, 2014; Trueman *et al.*, 2014; James *et al.*, 2016). This long-ignored deep "blue carbon" now appears to be a significant component of anthropogenic CO_2 sequestration (Boyd *et al.*, 2019).

WHAT KNOWLEDGE IS NEEDED TO ASSESS THREATS AND IDENTIFY EFFECTIVE PROTECTIVE MEASURES?

Research on the vulnerability of terrestrial and marine ecosystems to climate stressors has highlighted the complexity of physiological responses and acclimatization and adaptation capabilities, depending on species' life cycles, potential population migrations and geographical areas. The combination of ocean warming and other stress factors is a crucial element for marine species. The physiological tolerance thresholds of species to hypoxia depend, among other parameters, on temperature and CO_2 concentration (Pörtner, 2010). Adaptation to acidification, as demonstrated for several deep-water coral species, is, however, being undermined by rising temperature (Lunden *et al.*, 2014; Gori *et al.*, 2016).

Climate stress factors, temperature, acidity, oxygen, and nutrient resources must be assessed across the habitats currently occupied by these species and those likely to shelter them in the future, and their natural variability taken into account.

The spatial distribution of deep species is strongly influenced by abrupt transitions between oxygen-depleted waters and those more oxygenated at the surface or in the abyssal zone, along the continental slope, on seamount sides and canyon walls. Even minor changes in deep water temperature and oxygen gradients can cause dominant species turnover and change the entire ecosystem structure. Scientists have suggested that this occurred in the Antarctic Peninsula, where a two-tenths of a degree warming over 30 years allowed alien red king crabs to invade the ecosystem. This predator's distribution area on the continental margin has thus spread to the detriment of many species (Smith *et al.*, 2014).

There are many unknowns in establishing environmental management measures for industrial activities, supporting the development of sustainable economic activities, or implementing deep habitat conservation policies in national and international waters. The current state of knowledge is too fragmented to accurately anticipate the impacts of climate change and requires the expansion of deep-water observation programs on relevant spatial and temporal scales. Given the tools used, their very high cost, and the need for specialized technical expertise shared by too few countries, mapping the risk is out of reach at present. Biodiversity and productivity "hotspots" on the ocean floor are mostly composed of assemblages, with links ranging from a few tens of meters to a few kilometers. Furthermore, most deep ecosystems are subject to seasonal and episodic phenomena driving their proper functioning, such as food intake or deep-water ventilation (Danovaro *et al.*, 2004; Smith *et al.*, 2012; Soltwedel *et al.*, 2016).

Knowledge is currently largely lacking to better understand how these intermittent events influence species' interactions with each other and with their environment. In particular, there is a lack of multidecadal ecological studies for the most vulnerable ecosystems facing cumulative pressures of exploitation and climate change (Smith *et al.*, 2013).

Building realistic vulnerability scenarios and incorporating them into marine public policies is a challenge that will have to be taken up in order to address sustainable development issues and effectively assess the impacts of large-scale human activities on deep marine areas. New international regulations (*e.g.* regarding mining) and treaties (*e.g.*, on marine biodiversity beyond national jurisdiction), as well as environmental management and spatial planning will need to include the deep ocean's role in the global climate and its processes.

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Coral and climate change

Denis Allemand

WHAT IS A CORAL REEF?

Coral reefs are ecosystems typically found in shallow waters of the intertropical zone (approximately between 33° North and 30° South). The three-dimensional architecture of this ecosystem is formed by the building of calcareous skeletons of marine organisms, called reef-building corals (Cnidaria Scleractinia). They are cemented together by the biological activity of calcareous organisms (macro-algae, sponges, worms, mollusks, etc.). Coral is referred to as an "ecosystem engineer", while reefs are considered "biogenic" because they result from biological activity. Coral reefs are therefore an ecosystem built by their own inhabitants.

Depending on the calculation method, the total surface area of coral reefs varies from 284,300 km² (Smith, 1978) to 617,000 km² (Spalding *et al.*, 2001), therefore covering between 0.08 and 0.16% of the ocean surface. French reefs alone cover an area of 57,557 km². The largest coral structure is the Great Barrier Reef, which stretches over 2,300 km along the north coast of north-eastern Australia. It is considered to be the only living structure on Earth visible from space. The second-largest reef is New Caledonia's barrier reef, measuring 1,600 km long. These two barrier reefs have been included in the UNESCO World Heritage list (in 1981 and 2008, respectively).

Coral reefs come in different shapes and sizes, and were first described by Charles Darwin during his voyage aboard the HMS Beagle (Darwin, 1842):

- Fringing reefs: These follow coastlines, maintaining an active growth area offshore, and accumulating dead coral inshore, thus forming a platform reef that, over time, turns into a lagoon.
- Barrier reefs: The fringing reef becomes a barrier reef subsequent to the progressive sinking of an island. As a result, its lagoon expands and the reef extends away from the coast, up to 1 km.
- Atolls: These are the ultimate step in reef evolution, where the island has completely disappeared below the sea surface. Atolls preserve the island's initial circular shape. There are about 400 atolls in the world.

Reef growth is currently of 4 about kg of calcium carbonate ($CaCO_3$) per m² per year (Smith & Kinsey, 1976; Mallela & Perry, 2007) with high values of about 10 kg $CaCO_3$ per m² and per year (Chagos Archipelago, Perry *et al.*, 2015). However, values vary widely from one reef to another and, in some cases, can reach up to 35 kg $CaCO_3$ per m² per year (Barnes & Chalker, 1990), *i.e.* annual vertical growth rates from 1 mm to 20 cm, depending on the species (Tunnicliffe, 1983; Dullo, 2005). Many factors influence these growth rates: light, temperature (optimal between 22° and 29°C), nutrients, sea level, currents, turbidity, pH and calcium carbonate saturation state of seawater (Tambutté *et al.*, 2011, for review).

Calcium carbonate production by reef-building organisms releases carbon dioxide into the marine environment. Hence, contrary to what has long been believed, a reef mainly dominated by coral behaves as a minor source of CO_2, not as a sink (about 1.5 mmol CO_2/m²/day; Gattuso *et al.*, 1993; Tambutté *et al.*, 2011 for review). However, reefs do play a major role as a carbon sink with rates of approximately 70-90 million tonnes of carbon stored annually as $CaCO_3$ (Frankignoulle & Gattuso, 1993).

CORAL, AT THE ORIGIN OF REEFS

Reefs are mainly built by coral. Formerly called zoophyte because of its resemblance to plants, then Madreporaria, reef-building coral is now included in the order Scleractinia (subclass Hexacorallia, class Anthozoa, phylum Cnidaria). Currently, 1,610 valid species have been identified among Scleractinia ("Word List of Scleractinia", Hoeksema & Cairns, 2019; Cairns, 1999), about half of which are involved in reef construction. They are therefore referred to as hermatypic. This coral is composed of polyps of varying size, depending on the species, forming functional units (colonies), that operate as a single organism. For this reason, coral is sometimes referred to as a modular animal. Each polyp has a mouth surrounded by tentacles. Polyps are connected to each other by a network of cavities, called cœlenteron or gastrovascular cavity, running through the coral tissue. Seawater and nutrients circulate in these cavities. Cœlenteron performs many functions, including digestion and fluid circulation for breathing and nutrition.

Tissues are composed of two cell layers, the epidermis (or ectoderm) in contact with seawater and gastrodermis (or endoderm) in contact with the cœlenteron. These two layers are separated by an acellular matrix, called mesoglea. Together, they are shaped like a bag. Coral has a nervous system consisting of nerve fibers, without ganglion formation.

Coral presents various shapes and sizes depending on whether the species is a branching, blade, encrusting or stony coral. For instance, the latter can exceed 10 m in diameter (12 m for “Big Momma”, a giant *Porites* discovered in the National Marine Sanctuary of American Samoa in the Pacific Ocean, cf Brown *et al.*, 2009).

The degree of success for a reef to develop and thrive is mainly related to the ability of most scleractinians (just under 900 species, Michel Pichon, pers.comm.) to establish a mutual symbiosis with dinoflagellates — photosynthetic microalgae commonly known as zooxanthellae (*Symbiodinium* sp.). The latter can transfer 75-95% of their photosynthesis products to their animal host for its metabolism (Muscatine & Porter, 1977). Zooxanthellae are located inside coral's gastrodermal cells, isolated from the animal cytoplasm by a perisymbiotic membrane that regulates exchanges between the two partners (Furla *et al.*, 2011). While early research identified only one panmictic[1] zooxanthella species, *Symbiodinium microadriaticum* (Freudenthal 1962), new molecular tools have allowed scientists to discover nine clades in zooxanthellae, referred to as clades A-I (Pochon & Gates, 2010). Each has its own characteristics, suggesting that they could influence coral adaptation to a given environment. New studies in molecular phylogenetics now show that these clades are likely to correspond to different genera (Lajeunesse *et al.*, 2018).

There would thus be: *Symbiodinium* (clade A), *Breviolum* (clade B), *Cladocopium* (clade C), *Durusdinium* (clade D), *Effrenium* (clade E), *Fugacium* (clade F) and *Gerakladium* (clade G). All these genera belong to the family Symbiodiniaceae. This species diversification is thought to have occurred during the Jurassic period (approx. 160 million years ago), which corresponds to adaptive radiation of modern coral. This radiation follows an initial period of coral reef expansion, succeeded by a regression during the Triassic, about 240 million years ago (Muscatine *et al.*, 2005; Frankowiak *et al.*, 2016). This diversification was already linked to a photosynthetic symbiosis (Muscatine *et al.*, 2005), perhaps with Suessiaceae algae — considered to be the ancestors of modern dinoflagellates and now exclusively fossils (Frankowiak *et al.*, 2016; Janouškovec *et al.*, 2017).

The co-evolution between the cnidarian host and its dinoflagellate symbionts shaped the two partners' biology, physiology and morphology. They thus developed unique specific features, such as the

1 In population genetics, panmixia is the principle that considers individuals to be evenly distributed within a population and reproduce randomly.

animal host's ability to actively absorb CO_2 to fuel its symbionts' photosynthesis; resist hyperoxia and oxidative stress generated during oxygen production within its tissues; absorb mineral nitrogen compounds; protect itself against ultraviolet rays, etc. (Furla *et al.*, 2005, 2011 for review). Due to the presence of zooxanthellae, coral depth distribution depends on light, availability usually at depths between 0 and 30 m deep. However, some symbiotic coral species can live in very low light conditions down to 150 meters, thus constituting a mesophotic coral ecosystem. Exploration of these environments is just beginning, despite the fact that, they may constitute 80% of total reef habitats (Weiss, 2017). This coral could be a source of larvae to replant damaged surface reefs (Bongaerts *et al.*, 2010).

In addition to zooxanthellae, coral hosts many bacteria, the diversity of which has been highlighted using modern sequencing techniques. These bacteria appear to play a significant physiological role (Thompson *et al.*, 2014 for review).

The entire community of these living organisms forms a functional unit, called a holobiont, often referred to as a super-organism (Rohwer *et al.*, 2002). Symbiont photosynthesis is linked to another coral function, biomineralization, *i.e.* its ability to build a calcareous skeleton (biomineral). This is a composite material, comprising both a mineral and an organic fraction. Even though the latter is minor (< 1 % by weight), it plays a key role in controlling calcium carbonate deposition in the form of aragonite (Allemand *et al.*, 2011; Tambutté *et al.*, 2008, 2011). Using mechanisms that are still debatable, light, via symbiont photosynthesis, stimulates day calcification by a factor of up to 127 compared with night calcification. However, in most cases, this factor varies between 1 and 5, with an average value of 4 (Gattuso *et al.*, 1999).

Coral usually reproduces sexually and involves a larval stage, called planula, which ensures species dispersal. It also has high asexual reproductive capabilities by fragmentation and budding — a property used to develop *ex situ* cultures.

CORAL, CORALS

The word "coral" entails a plurality of species belonging to the phylum Cnidaria and forming the basis of several ecosystems:

- Cold-water corals, also known as deep-water corals: These belong to the same order in the phylum Cnidaria as reef-building corals (Scleractinia). Like them, they are ecosystem engineers, capable of building a rich ecosystem that provides a habitat for many other organisms in the deep waters of the Atlantic and Pacific Oceans, and also the Mediterranean Sea. Unlike their shallow-water cousins, they are acclimatized to cold waters (6°-14°C) and do not host photosynthetic algae. These deep reefs therefore play a significant role as shelters and nursery for many fish species of commercial importance (Roberts *et al.*, 2009).
- Mesophotic corals: These also belong to the order Scleractinia, live at a depth of between 30 and 150 meters and are symbiotic. They form a continuum with surface corals (cf.supra).
- The coralligenous in the Mediterranean Sea:Composed of an assemblage of sessile organisms (*e.g.* sea fans, red coral, encrusting calcareous algae, etc.), this forms a very rich coastal ecosystem built on underwater cliffs. It is of particular interest both for fishing and aquatic tourism (Regional Activity Centre for Specially Protected Areas - RAC/SPA, 2003).

CORAL REEF: A BIODIVERSITY HOTSPOT

The ability to live in symbiosis with dinoflagellates has enabled coral to build large reef structures in usually oligotrophic areas, *i.e.* nutrient-poor waters. Coral reefs have existed in various forms since the Triassic, about 240 million years ago. However, since that time, many phases of disappearance/resurgence have occurred. The construction of the Great Barrier Reef is estimated to have begun 20 million years ago. However, primitive forms, different from modern coral, existed long before the Triassic, during the Devonian, about 400 million years ago.

Coral reefs are home to the greatest biological diversity on Earth, with 32 of the 34 animal phyla known to date, and include one-third of the marine species currently identified, representing nearly 100,000 species (Porter & Tougas, 2001). Hence, 30% of the known marine biodiversity inhabits less than 0.2% of the total ocean surface. In the marine environment, coral reefs are therefore the equivalent of primary tropical forests. As a comparison, the number of mollusk species found on 10 m² of reef in the South Pacific Ocean exceeds the total number of species identified throughout the North Sea. To give another example, in New Caledonia there are over 400 species of coastal nudibranchs, while on mainland France, there is only a dozen species for an equivalent coastline.

However, this biodiversity is not homogeneous between reefs. In fact, there is a skewed distribution of coral diversity and abundance between the Atlantic and Pacific, as well as within these oceans. In both oceans, the diversity and abundance are concentrated in the western parts: the Coral Triangle (also called the "Center for Coral Biodiversity") in the Pacific, including the Malaysia-Indonesia- Philippines-China Sea-Solomon Islands region, and the Caribbean zone in the Atlantic. There is also a strong west-east longitudinal gradient. The fauna and flora associated with reefs generally follow similar gradients.

CORAL REEF: AN EXCEPTIONAL TREASURE FOR HUMANITY

Coral reefs border the coasts of more than 80 countries across the world (Sheppard *et al.*, 2009), for which they represent an important source of income in terms of food resources, coastal protection, tourism, etc. Approximately 275 million people worldwide live within 30 km of a coral reef and the livelihood of over 500 million people directly depends on reefs (Wilkinson, 2008). On the one hand, economists estimate that the annual value of the services provided by reefs is worth just over 24 billion euros (Chen *et al.*, 2015). On the other hand, the Economics of Ecosystems and Biodiversity report (TEEB, 2010) estimated that the destruction of coral reefs would represent a loss of about 140 billion euros per year.

The ecosystem services provided by coral reefs include:

- Natural resources:
    1. **Food:** Coral reefs provide 9-12% of fish catch worldwide and 20-25% in developing countries ((Moberg & Folke, 1999). This figure reaches 70-90% in South-East Asian countries (Garcia & de Leiva Moreno, 2003). The total estimated income of reef fisheries is 5 billion euros (Conservation International, 2008). Most of these fisheries are traditional, carried out on foot by the local population, mainly women and children collecting fish, mollusks (giant clams), crustaceans (crabs and lobsters) and sea cucumber (also referred to as trepang). A healthy reef is estimated to annually provide 10 to 15 tonnes of fish and invertebrates per km².
    2. **Mineral resources:** Coral reefs provide house building materials (Maldives, Indonesia), sand to build road infrastructure,fertilizers for cropland, etc. Coral reefs in the Maldives thus supply about 20,000 m^3 of material annually (Moberg & Folke, 1999).
    3. **Living resources:** Beyond food fishery, reefs also represent a fishing reserve for coral reef aquariology (15 million fish per year for 2 million aquarists worldwide), pearl farming, etc.
- Conservation:
    1. **Coastal protection:** Coral reefs strongly contribute to protecting coastlines from the destructive action of waves and tsunamis. More than 150,000 km of coastline are naturally protected by barrier reefs (http://www.coralguardian.org). A typical coral reef can absorb up to 97% of wave impact forces (Ferrario *et al.*, 2014). During the devastating 2004 tsunami in the Indian Ocean, coasts protected by healthy coral reefs were much less affected by the deadly wave (IFRECOR, 2010). The value of coastal

protection against natural disasters has been estimated at between 20,000 and 27,000 euros per year per hectare of coral (TEEB, 2010). The total estimated benefit is 7 billion euros per year (Conservation International, 2008).

- Cultural resources:
  1. **Tourism:** The large number of visitors attracted to the natural beauty of coral reefs (seaside tourism, diving) promotes employment in often poor regions. For example, the Great Barrier Reef attracts some 2 million visitors each year, generating revenues of about 4 billion euros for the Australian economy and supporting 64,000 local jobs (Deloitte Access Economics, 2017). According to estimates compiled in the TEEB report (TEEB, 2010), one hectare of coral reef represents a yearly profit of 64,000 to 80,000 euros from tourism and leisure activities. Ecotourism alone earns 800,000 euros per year in the Caribbean. Approximately 2.5 million visitors per year enjoy the tropical coastal area in Egypt; 23% coming specifically for the coral reefs and 33% engaging in diving activities (Cesar *et al.*, 2003; Hilmi *et al.*, 2018a). Coral reef-related tourism is particularly important for the economy of small island developing States (SIDS). In total, more than 100 countries and territories benefit from coral reef-related tourism and for 23 of them, this income represents more than 15% of their gross domestic product (GDP) (Burke *et al.*, 2011). The total annual income from coral reefs worldwide is estimated to be around 8 billion euros (Conservation International, 2008), and represents about 30% of reef revenues and 9% of the global coastal tourism (Spalding *et al.*, 2017). Coral reef-related tourism is constantly and steadily growing by about 20% per year, *i.e.* four times faster than global tourism (Cesar *et al.*, 2003). However, this sector is very sensitive to reef health, with a fall in revenues of about 20-30% where reefs undergo bleaching episodes (UN Environment *et al.*, 2018; Woodhead *et al.*, 2019).
  2. **Cultural or religious heritage:** Coral reefs sustain many cultural and religious traditions. In southern Kenya, for instance, many religious rituals are organized around coral reefs to appease the spirits (Moberg & Folke, 1999).
  3. **Medical resources and biological models:** The numerous marine invertebrates (sponges, mollusks and soft corals) represent a considerable source of chimiodiversity for future drugs (Bruckner 2002). Coral is also starting to be used as a biological model to better understand immunity or aging mechanisms (Moberg & Folke, 1999).

CORAL REEF: LOCAL AND GLOBAL THREATS

Coral reef ecosystems have been threatened globally since the 1980s (global warming, ocean acidification) and are now also impacted locally (pollution, sedimentation, unsustainable coastal development, nutrient enrichment, overfishing, use of destructive fishing methods, etc.). The Global Coral Reef Monitoring Network (GCRMN) currently estimates that 19% of reefs have been destroyed, 15% are seriously damaged and may disappear within a decade, and 20% are at risk of disappearing within the next 40 years. The rare monitoring studies on reef growth show a clear long-term decrease in coral cover: in an analysis of 2,258 measurements performed on 214 reefs of the Great Barrier Reef during the 1985-2012 period, De'ath *et al.* (2012) highlighted a decline in coral cover from 28% down to 13.8%, and a loss of 50.7% of the initial coral cover.

Among the global events affecting coral reefs, the most significant today is the rising surface water temperature (physical stress factor), causing a widespread phenomenon, known as coral bleaching (see

Ezzat in the present document). This disturbance, the only example, visible to the naked eye of the impact of climate change on an ecosystem is the result of the symbiosis cleavage between coral and its zooxanthellae symbionts. Although they can be reversible during the first few days, bleaching events inevitably lead to coral death within a few weeks of the cleavage (Hoegh-Guldberg, 1999; Weis & Allemand, 2009). This phenomenon, the inner mechanisms of which are still under debate, usually occurs when water temperature exceeds a certain threshold (usually around 28°C) by 0.5°C. However, it very much depends on geographical area (Coles & Riegl, 2013) and species (Loya *et al*., 2001).

Beyond the direct impacts of bleaching episodes on coral physiology and survival, a recent study showed that the organisms affected by bleaching have a reduced reproductive capacity, making coral reef resilience even more difficult (Hughes *et al*., 2019).

A second event is just as seriously affecting coral biology: ocean acidification, also referred to as the other CO_2 effect (Doney *et al*., 2009). This alteration is chemical. Part of the excess carbon dioxide produced by human activities dissolves into the ocean, thus reducing the greenhouse effect (and the rise in global temperature), but also increasing ocean acidity, according to the following reaction: $H_2O + CO_2 \leftrightarrow HCO_3^- + H^+$

To date, seawater pH has decreased by about 0.1 pH units (from 8.2 to 8.1) since the beginning of last century. This corresponds to an increase in water acidity by about 30% (Gattuso & Hansson, 2011). Acidification primarily affects coral calcification rates, and therefore reef growth. However, the effects vary greatly from one species to another, without ever exceeding an inhibition rate of 50% for the same value of CO_2 (Erez *et al*., 2011). Differences in sensitivity may be due to the differential ability of coral to control pH at the site of calcification (Venn *et al*., 2013; Holcomb *et al*., 2014). However, the increase in dissolved CO_2 causes many other effects on coral physiology, including the alteration of gene expression (Moya *et al*., 2012; Vidal-Dupiol *et al*., 2013).

Unfortunately, our present knowledge of coral physiology is too incomplete to predict whether these organisms will be able to adapt to rapid changes in their environment, especially since earlier studies suggested that the combined effects of decreased pH with temperature rise seem to have cumulative impacts (Reynaud *et al*., 2003). For some researchers, the rate of climate change is too rapid to enable long-term genetic adaptation in populations with long generation times (Veron *et al*., 2009). However, signs of physiological acclimatization processes have been identified (Kenkel & Matz, 2016).

The fact that some coral populations are naturally able to withstand much higher temperatures without showing signs of bleaching, such as those of the Persian Gulf which only start bleaching above 34-35°C (Riegl *et al*., 2011), suggests that adaptation to global warming is possible. Similarly, some coral populations naturally living in more acidic waters than the ocean average, as for instance in Palau (pH=7.8 vs. 8.1), are quite capable of maintaining a high coral cover (Shamberger *et al*., 2014). Unfortunately, this potential adaptation to ocean acidification is not found on other sites; In Papua New Guinea, for example, branching corals have almost disappeared and a profound alteration of reef functioning can be observed (Fabricius *et al*., 2011). Recent laboratory studies have shown that coral subjected to a pH of about 7.2 was able to maintain a similar axial growth to control specimens kept at a pH of 8.1. In order to do so, the coral skeleton becomes much more porous (Tambutté *et al*., 2015). Field observations confirm these experimental results (Rippe *et al*., 2018). An epigenetic modification of specific gene expression is believed to cause this adaptation (Liew *et al*., 2018a). As in other organisms, this type of modification can be passed down to future generations (Liew *et al*., 2018b). This mechanism optimizes gene expression in response to changing environmental conditions. However, this adaptation can have negative consequences, making coral branches more fragile.

Improving our scientific knowledge of coral reefs is therefore necessary to predict their future. Indeed, behind a simple anatomy, coral conceals a high degree of physiological complexity. Isn't the number of their genes actually similar to that of humans?

Without being as pessimistic as the recent IPCC Special Report (IPCC, 2018), which predicts that 2°C warming would destroy almost all coral reefs (99%), it is safe to say that, by 2100, reefs will be different from those existing today.

SOLUTIONS TO ENSURE REEF SURVIVAL IN THE 21ST CENTURY

The scientific community and politicians are now concerned about the future of reefs. This is driving international actions, such as the recent Coral Reef Life Declaration launched in 2017 at the "Our Ocean, an ocean for life" conference by HSH Prince Albert II, HRH the Prince of Wales and HM Queen Noor of Jordan (https://www.fpa2.org/details_actualite.php?idactu=6761&lang=en). The two recent workshops held in Monaco on solutions to save coral reefs (Hilmi *et al.*, 2018b; Allemand & Osborn, 2019) concluded that actions will necessarily require the simultaneous implementation of local and global solutions (including the drastic reduction of greenhouse gas emissions). Among the local solutions, these workshops highlighted:

- **Mitigation**: Mitigation procedures aim to stabilize greenhouse gas concentrations by tackling the causes of climate change, such as reducing carbon dioxide emissions. Most of these solutions are not specific to coral reefs and include seagrass restoration or culture, and mangrove replanting. In fact, these ecosystems are particularly effective CO_2 sinks, locally mitigating the decrease in pH due to ocean acidification (Fourqurean *et al.*, 2012; Howard *et al.*, 2017). Marine geoengineering solutions have also been proposed, such as adding alkaline materials to seawater (Hilmi *et al.*, 2015 for review) or dispersing on the ocean surface biodegradable biopolymers capable of limiting light penetration.
- **Protection**: The creation of Marine Protected Areas (MPAs) has repeatedly been suggested as an effective way to reduce local stress factors and increase resilience to global changes (Hilmi *et al.*, 2015). The role of MPAs in mitigating, adapting and protecting coral reefs is supported by numerous scientific studies (Ban *et al.*, 2011; Roberts *et al.*, 2017). However, less than 6% of coral species are effectively protected by MPAs today (*i.e.* less than 10% of their distribution area, Mouillot *et al.*, 2016). Furthermore, MPAs do not ensure fully effective protection against global changes. Indeed, the northwest Great Barrier Reef, although protected and far from any direct anthropogenic impact, suffered a significant bleaching event (90%) in 2015-2016 (Hughes *et al.*, 2017). One solution would be to promote the protection of "refuge" areas where corals are stronger than in normal areas, such as the Persian Gulf (Coles & Riegl, 2013; Howells *et al.*, 2016), the Red Sea (Fine *et al.*, 2013, 2019; Osman *et al.*, 2017) or the mesophotic zone at depths between 30 and 150 m (Bongaerts *et al.*, 2010). The creation of a Global Coral Conservatory to preserve species for possible reef restoration or scientific purposes has also been proposed (Zoccola D., pers. comm.), as well as the development of scientific research on coral resistance (Conservation Physiology, Wikelski & Cooke, 2006). A coral conservatory would also help scientists select resistant strains using the assisted evolution method (van Oppen *et al.*, 2015) and artificial reproduction (West & Salm, 2003).
- **Adaptation**: Among the adaptation solutions available to reef areas, promoting a "blue" economy (tourism, fisheries, agriculture) that embodies sustainability principles is essential. In many areas, reducing tourist pressure on reefs, either by regulating diving activities (Hasler & Ott, 2008) or by creating artificial reefs accessible to recreational divers (Kotb, 2016) can also be beneficial. The creation of the Cancún Underwater Museum (MUSA, Mexico), inaugurated in 2010 with 450 underwater sculptures, is a step in the right direction, as is the use of eco-designed mooring buoys (ICRI, 2017) .

- **Restoration**: The final category focuses on restoring deteriorated reef ecosystems, by introducing colonies collected in "refuge" areas, such as the Persian Gulf (see above, Coles & Riegl, 2013) or: *i) ex situ* reared coral using coral fragments resulting from asexual reproduction (Global Coral Conservatory, Rinkevich, 2005, Leal *et al.*, 2014; Allemand, 2014); *ii)* juveniles resulting from sexual reproduction (Nakamura *et al.*, 2011), or *iii)* using *in situ* culture (Kotb, 2016; Rinkevich, 2005, 2014).

While growing, resistant coral strains could be "selected" through an "assisted evolution" process (van Oppen *et al.*, 2015). These authors suggest assisting coral in evolving towards greater resilience. To that end, they propose four options: The first aims to enhance resistance by artificially inducing stress in the laboratory and keeping only the colonies that survive (preconditioning acclimatization). This process is mediated by epigenetic mechanisms (cf. supra). The second option is to actively modify the microbiota associated with coral to select the most resilient community (Peixoto *et al.*, 2017). The third is to select specific organisms to generate resistant phenotypes. The last option is to artificially change the algal component of the coral holobiont by mutation and the genetic selection of zooxanthellae, and inoculate coral with resistant strains of zooxanthellae (Hume *et al.*, 2015). Coral can then be transplanted to natural or artificial reefs. The Reef Ball Foundation, a non-profit organization, has developed specific protocols for deploying, fixing and transplanting coral. Biorock is a patented method that uses electrolytic deposition of calcium carbonate to build artificial structures (Goreau & Hilbertz, 2005). The French NGO Coral Guardian is developing reef restoration programs. While reducing costs, these programs contribute to enhancing local communities' involvement in accelerating sustainable development mechanisms in order to improve their livelihoods.

Coral reefs play a major ecological and socio-economic role. Yet they are currently one of the most threatened ecosystems in the world. The development of original economic, technical and political methodologies is not only necessary to save this iconic ecosystem, but will also provide an action model applicable to other ecosystems.

It is crucial that these methodologies are based on scientific research, developed both in laboratories and *in situ*. The Tara Pacific expedition (https://oceans.taraexpeditions.org/m/qui-est-tara/les-expeditions/tara-pacific/) is an excellent example: dedicated to better understanding the Pacific Ocean reefs, this mission also aims to propose practical solutions to increase their resilience and survival rate.

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Coral bleaching, an imminent threat to marine biodiversity

Leïla Ezzat

For thirty years, the ocean mean temperature has been incessantly increasing, which reinforces the intensity and length of coral bleaching. The period between 2014 and 2017 was marked by massive coral mortality in the various ocean basins, with an exceptional decline by more than 50% in the reefs on the Great Barrier Reef – the largest coral structure in existence. Coral resilience was compromised with a low recruitment rate of coral larvae, and the stress experienced was exacerbated by additional anthropogenic factors (pollution, overfishing, urbanization, tourism, ocean acidification, predation by corallivores, etc.). 2018 has been the warmest year for the oceans since records began, suggesting that coral bleaching could become a recurrent phenomenon in the years to come. In order to protect this natural heritage, which is home to more than a third of the global marine biodiversity and on which over 500 million people depend worldwide for their livelihoods, it is necessary and urgent for governments to take action, beyond local measures, towards reducing human impacts on climate.

Despite their ecological and economic importance, coral reefs are affected by many stress factors at both a local level (marine resource overexploitation, destructive fishing methods, tourist pressure, marine pollution, coastal development, predation by corallivores, etc.) and a global level (rising ocean surface temperature, extreme weather events, ocean acidification) [1-4]. Anthropogenic pressure and climate change currently threaten most reef ecosystems around the world. Over time, these stress factors can lead to a rupture between the coral host and its photosynthetic symbionts – a phenomenon referred to as "bleaching" because coral progressively whitens as it loses its symbionts and/or associated photosynthetic pigments [5]. A moderate decrease in the concentration of symbionts and/or associated photopigments is due to a seasonal and natural phenomenon. This occurs when surface water temperature exceeds seasonal mean maximum temperature over a short period of time which varies according to observed sites.

However, for thirty years, the mean ocean temperature has been rising at an abnormal pace, increasing the duration, intensity and extent of coral bleaching [6]. As a result of the loss of its photosynthetic symbionts, which are its main food source, coral is "physiologically" weakened. In the event of an extended bleaching episode, coral dies of nutritional stress, leading to massive mortality in reef ecosystems worldwide, from the Pacific to the Indian Ocean, the Caribbean, and the Red Sea.

HISTORY OF CORAL BLEACHING

The first coral bleaching episode was seemingly reported by Yonge and Nicholls regarding the Great Barrier Reef in the 1930s, when surface water temperature was 35°C [7]. Since the 1980s, scientists have observed an increase in the frequency, intensity and extent of bleaching episodes worldwide [5]. This is caused by a "record" increase in ocean surface temperature due to global warming, combined with the reinforcement of the El Niño phenomenon. Three major bleaching events were reported in 1998-1999, 2010-2011 and 2014-2017. The 1998 episode impacted 60 countries and island nations across the Pacific, Indian and Atlantic Oceans (Caribbean region), the Persian Gulf and the Red Sea [8,9]. The areas covering the Indian Ocean were particularly affected, with over 70% coral mortality observed over a gradient depth up to 50 m [9]. Significant ocean surface temperature anomalies caused a loss of more than 16% of coral reefs around the world [5]. In fact, 1998 was the first "global bleaching episode" declared by National Oceanic and Atmospheric Administration (NOAA).

Again, in 2010, an intense El Niño phenomenon triggered another extreme coral bleaching event, affecting all reefs across the world with, in some regions such as South-East Asia, greater consequences in terms of expansion and mortality.

The 2014-2017 bleaching event was of exceptional and unprecedented magnitude, duration, and extent. This third bleaching episode began in June 2014 in the western Pacific (Guam, the Mariana Islands and Hawaii), then spread to the Marshall Islands and the Florida Keys. In 2015, the phenomenon extended to the South Pacific, the Indian Ocean, the central and eastern regions of the tropical Pacific, and finally the Caribbean. By the end of 2015, when El Niño was reaching its peak, 32% of the world's reefs had been exposed to a temperature anomaly of +4°C, causing coral mortality over more than 12,000 km². In March 2016, the mean seawater temperature in the northern Great Barrier Reef was 1.5 to 2°C higher than the values recorded between 1971 and 2000 at the same time of year. This global bleaching episode affected more reefs than previous events and was particularly damaging in some areas, such as the Great Barrier Reef and the Kiribati and Jarvis Islands in the Pacific Ocean.

More than 70% of coral reefs around the world were affected by the heat wave that led to bleaching and mortality episodes between 2014 and 2017. Historically, coral bleaching has been linked to the natural El Niño cycle – a climate phenomenon characterized by high seawater temperature – in the eastern South Pacific (South America) and to an atmospheric pressure variation cycle in the South Pacific (Southern Oscillation). The last bleaching event (2014-2017) was particularly dramatic, because it was not continuously linked to El Niño episodes (for example, 2017 was a year dominated by La Niña), suggesting that, unlike previous events, the Southern Oscillation had very little impact on coral bleaching.

ALARMING CONSEQUENCES OF THE 2014-2017 BLEACHING EPISODE

Massive coral mortality across the world oceans

In 2016, aerial and underwater exploration programs showed that out of a total of 911 individual reefs observed on the Great Barrier Reef, 93% had been affected, in particular 1,000 km along the coast north of Port Douglas – an area away from human activities, considered perfectly preserved until then [10]. In contrast, in the central region, between Cairns and Mackay, the bleaching was moderate. The southern area was spared due to a drop in seawater temperatures resulting from Cyclone Winston. In 2017, for the second consecutive year, a bleaching episode severely impacted the Great Barrier Reef and more specifically the central area, near Cairns, Townsville and Lizard Island. More than 50% of the reefs composing the Great Barrier Reef died between 2016 and 2017 [11], including centuries-old species, such as *Porites* coral [10]. Guam, the largest island in Micronesia located east-southeast of the Philippine Sea, underwent extreme bleaching episodes for four consecutive years.

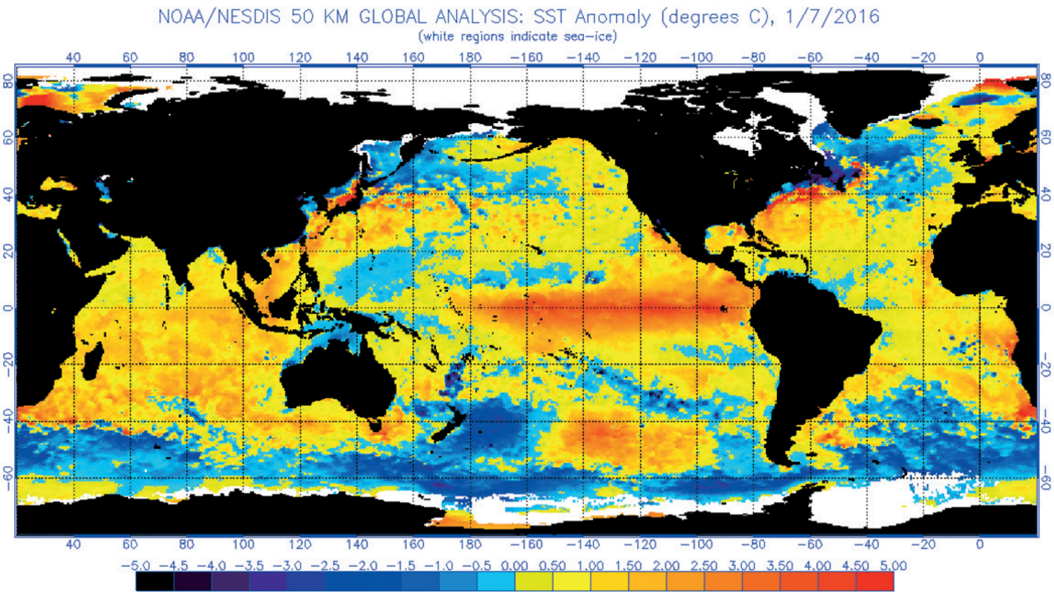

Fig.1 — Sea surface temperature anomalies (°C). The scale ranges from -5°C to +5°C. Positive numbers mean that the temperature calculated on 7/1/2016 was above average.

The phenomenon was severe in the Coral Triangle (Malaysia, Indonesia, the Philippines, and the Solomon Islands), New Caledonia, Fiji and Kiribati, where unusually high seawater temperatures caused more than 80% coral mortality around Christmas Island in 2015-2016. Significant temperature anomalies were also recorded in China, Vietnam, Taiwan, and particularly in Japan, in the Sekiseishoko reef area, where 97% of coral mortality was reported at the end of 2016. Over the past three years, more than 20% of the reefs across the world have disappeared.

Impacts of coral bleaching on the abundance and diversity of reef fish

Coral reefs, often described as cradles of the global marine biodiversity, are home to more than a third of all marine organisms, including 4,000 fish species. However, when reef-building coral undergoes bleaching and dies, a whole biodiversity reservoir is endangered. Following the 2016 heat wave, scientists reported a decrease in the abundance and diversity of herbivorous fish species [12,13], such as damselfish in parts of the Great Barrier Reef [12]. The decline in herbivorous communities is all the more worrying as they play a key functional role in reef development, survival and resilience by consuming the filamentous algae that colonize coral [14].

Nevertheless, it should be noted that the decline in some herbivorous species was not always correlated with a decrease in coral cover [12]. In some areas, experts have observed an increase in the abundance of herbivorous fish, suggesting significant spatial movements and potential short-term "climate refuges".

Compromised recruitment of coral larvae The consequences of recent bleaching events could compromise coral's ability to reproduce. During the 2016-2017 bleaching episodes, the sharp decline in adult individuals of reef-building coral in the northern and central Great Barrier Reef resulted in an 89% drop in larval production compared with the 2016-2017 pre-bleaching periods [15]. Acropora coral – one of the most abundant taxa in the tropics, responsible for the three-dimensional structure of a reef – was the most affected species with a 93% fall in larval production. These observations are alarming, since the quantity of coral larvae produced each year and their dispersal prior to medium/substrate colonization are key elements of reef resilience. The diversity of coral larvae will therefore greatly influence that of future "adult" colonies. "We expect coral recruitment will gradually recover over the next five to ten years as surviving corals grow and more of them reach sexual maturity, assuming, of course, that they do not experience another bleaching event in the coming decade," said Professor Terry Hughes, Director of the Australian Research Council (ARC) – Center of Excellence for Coral Reef Studies.

THE FUTURE OF CORAL REEFS: TOWARDS AN ANNUAL BLEACHING EPISODE?

In February 2019, the global mean ocean surface temperature was 0.7°C higher than the 20th century averages. Climate models predict a short-term extension of the El Niño phenomenon until late spring 2019 (northern hemisphere), thus significantly increasing coral susceptibility to a new bleaching episode and massive mortality. In the event that no action is taken by governments to keep atmospheric temperatures below the +1.5°C threshold in compliance with the Paris Agreement on climate change, experts predict that ocean surface warming could be six times more intense between 2081 and 2100 than the total warming observed over the past 60 years [6]. In fact, until recently, temperatures only rarely and intermittently exceeded the thermotolerance threshold limit above which coral bleaches. However, scientists expect this phenomenon to occur on an annual or biannual basis, thus threatening the survival of coral reefs around the world by 2050. These predictions are alarming because an increase in bleaching intensity, extent and frequency, such as that observed in the Caribbean (1995, 1998, 2005 and 2010) and on the Great Barrier Reef (1998, 2010, 2014-2016 and 2017) for instance, limit reef ecosystem resilience and can lead to higher mortality rates in the long term.

Recent studies have, however, highlighted that some coral species have developed mechanisms and potential for acclimatization to high temperature anomalies. A team of American scientists recently compiled data from the four major bleaching events (1998-2017), encompassing 3,351 sites across 81 countries. They observed that the phenomenon was significantly less pronounced in reefs characterized by a large variation in surface water temperature [16]. Also, some reefs were particularly resistant to the latest heat waves, such as those around the Palmyra Atoll (90% survival rate) in the Northern Line Islands [17], the Indonesian archipelago of Rajat Ampat, or the Gulf of Aqaba in the Red Sea, described as a unique coral refuge [18,19].

From a physiological perspective, some coral species are better able to resist bleaching, such as stony reef-building coral, characterized by slow growth and thick tissue (for instance, taxa from the families Faviidae and Poritidae or Merulinidae). In contrast, branching coral, belonging to the families Pocilloporidae and Acroporidae, is generally more sensitive to strong temperature anomalies [20-22]. Some species may associate with different clades of symbiotic algae to optimize their resistance to thermal stress or regulate their gene expression to strengthen defense mechanisms (genetic diversity) [23-25]. A recent study also demonstrated potential for ecological memory of bleaching, making some coral species potentially more resistant to future events [26]. However, coral resilience remains low and the time required to adapt or acclimatize to thermal stress is too short. These different mechanisms are therefore unlikely to play a major role in reef survival. Finally, other stress factors must be taken into account to accurately predict future development of reef ecosystems. The synergetic effect of some factors (*e.g.* marine pollution and overfishing) can alter trophic relationships between organisms within a reef, increasing coral susceptibility to bleaching, disease, and mortality. For example, during periods of thermal stress, predation by corallivores (*i.e.* sea stars, snails, reef fish) physiologically weakens coral, decreasing its long-term resilience to climate change and other stress factors [27-29].

URGENT NEED FOR ACTION

These recent events have caused concern among the scientific community and heightened collective awareness of the need to act quickly in order to reduce human impact on climate and preserve coral reefs.

In 2016, the Paris Agreement – the first universal agreement on global warming – was signed following the negotiations held at the Paris Climate Change Conference (COP21) in December 2015.

This agreement, which aims to "hold the increase in the global average temperature to below +2°C above pre-industrial levels by 2100" and, if possible, "pursue efforts to limit the temperature increase to 1.5°C", was approved by 196 out of the 197 United Nations (UN) delegations. Moreover, the European Union, in collaboration with the European Environment Agency, set a significant number of environmental and climate objectives encompassing the areas of air and water quality, waste management, energy and transport. At the end of 2018, the Intergovernmental Panel on Climate Change (IPCC) presented a Special Report on "Global Warming of 1.5°C" reminding government authorities of the urgent need for swift action to reduce greenhouse gas emissions. At the current rate, global warming will reach +1.5°C between 2030 and 2052. France alone accounts for 10% of the world's reefs (58,000 km²) and is committed at national level to improving the conservation status of French coral reefs and ensuring their sustainable management through the French Coral Reef Initiative (IFRECOR). At international level, the French government is involved in the International Coral Reef Initiative (ICRI), promoting initiatives and projects to ensure coastal ecosystem protection. Following the signing of the Brussels Declaration "Climate Change and Ocean Preservation" (February 2019), France reiterated its international commitments on sustainable development, climate change and ocean biodiversity preservation.

New techniques and numerous resources have also been implemented to monitor global warming and its impact on coral reefs. For instance, the "Catlin Seaview Survey" expedition, launched in September 2012, monitors the status of coral reefs around the world.

This campaign preceded the production of the documentary "Chasing Corals" (Jeff Orlowski), chronicling the onset and development of the third coral bleaching episode in the various ocean basins, using powerful videos and images that raised awareness among the general public. The Scripps Research Institute in San Diego recently launched the "100 Island Challenge" project, aiming to map 100 coral reefs in order to better understand the impact of climate change and human stressors on this ecosystem. The researchers studied a dataset of thousands of images from the same reef area collected over 8 years. These photographs were assembled using software to create 3D photo mosaics and demonstrated the resilience of Palmyra reefs in the Pacific Ocean following the 2014-2016 bleaching episode. In the same vein, the research schooner Tara sailed more than 100,000 km between 2016 and 2018 as part of the Tara Pacific expedition (led by the CNRS and the Centre scientifique de Monaco – CSM). The aim was to carry out an unprecedented study of reef biodiversity and its "resistance, adaptation, and resilience" abilities in the face of anthropogenic stress factors, using state-of-the-art technology.

These projects also led to numerous conferences and outreach campaigns to inform local populations, and the general public about the challenges facing the oceans. For example, the non-governmental organization "Reef Check" trains volunteer scientific divers to conduct transects in order to monitor the health status of tropical reefs around the world, as well as those stretching along the west coast of California.

The efforts made by these various organizations and governments can lead to the implementation of local actions to reduce human impacts on reef ecosystems. For instance, Mumby & Harborne (2010) [30] proved the effectiveness of marine protected areas (MPAs) for reef resilience in the Caribbean. In 2014, New Caledonia announced the creation of the "Natural Park of the Coral Sea", one of the biggest MPAs in the world (1.3 million km²). According to the Protected Planet Report, 7% of the total ocean surface was classified as "protected" in 2018. MPAs are therefore invaluable refuges to mitigate the decline in biodiversity observed since the 1970s. A recent study also demonstrated the positive effect of the diversity of coral species (polyculture, such as those observed in a healthy reef or a MPA) on coral growth and survival compared with decreasing biodiversity, characterized by a reduction in the number of coral species (monoculture; as observed

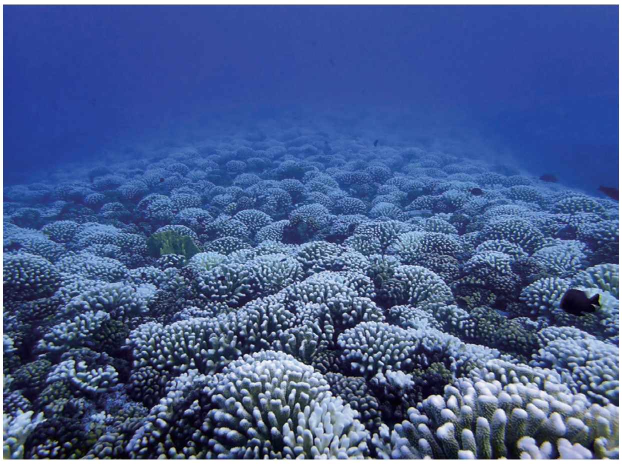

Fig.2 — Coral bleaching in April 2019 in Moorea, French Polynesia. © Kelly Speare, PhD student at the University of California, Santa Barbara.

in a damaged reef) [31]. Moreover, coral planting and reef restoration projects, such as those developed by the NGO "Coral Guardian", both stimulate marine life by promoting the recruitment of coral larvae and create new nurseries for marine organisms.

Biological engineering solutions have also been proposed, suggesting the use of "optimized" coral colonies under new environmental conditions to restore deteriorated reefs. Some scientists suggest using "assisted evolution" techniques to modify coral resilience threshold by performing laboratory artificial selection, which involves exposing coral to various stress factors or selecting thermo-tolerant symbiont stem cells [32].

However, these methods are still very expensive and would be difficult to implement on a large scale, given the enormous area occupied by coral reefs (the Great Barrier Reef alone extends over more than 2,300 km). Finally, at the end of March 2019, in Monaco hosted the first Steering Committee meeting of the World Coral Conservatory project, a program supported by the Prince Albert II of Monaco Foundation, and coordinated by the Centre scientifique de Monaco (CSM) and the Oceanographic Institute, Prince Albert I of Monaco Foundation. This initiative, bringing together research laboratories and public and private aquariums around the world, proposes creating a "Noah's Ark" of most coral species and strains – a way to preserve biodiversity within coral ecosystems by linking scientific research, conservation and awareness-raising.

Coral reefs are currently home to more than a third of the world's marine biodiversity and represent a protein source for more than 500 million people worldwide. According to Professor Terry Hughes, there is only one way to preserve marine life: "[We must] tackle the root cause of global heating by reducing net greenhouse gas emissions to zero as quickly as possible". Designing innovative projects that include scientific, political and social components will reduce our carbon footprint and ensure a future for our planet's ecosystems and for future generations.

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Ocean, biodiversity and climate

Gilles Boeuf

THE OCEAN

The ocean is the largest living space on the planet and at present covers 70.8% of the Earth's surface – *i.e.* 361 million km². But we should really think in terms of volume – around 1,370 million km³. The average depth is about 3,800 m and the main feature of this enormous environment is its continuity, leading us to think of a global ocean rather than several individual oceans. The Ocean is unique and ecologically connected! Another specific feature, compared with the rest of the water on the planet, is its salinity. The ocean's salinity offshore is extremely stable (35 psu, 1,050 mOsm.l^{-1}), and seawater composition is almost the same everywhere, as it has been for tens of millions of years. The ocean is therefore much more stable than any other living environment.

Biodiversity cannot be likened to a simple list of species inhabiting a particular ecosystem. It is considerably more than a catalog or inventory, and in fact includes all relationships between living beings, among themselves and with their environment. We can define it simply as being the living part of nature. Biodiversity comes from prebiotic chemistry, built upon earlier geodiversity. It became diversified in the ancestral ocean, around 3.9 billion years ago. Life appeared rather quickly, after the initial cooling and condensation of water masses.

Christian de Duve (Nobel Laureate, 1974) said in "Vital Dust" (1996) that the Earth was so ideally positioned in relation to the Sun, that life could not fail to appear there, and Jacques Monod spoke about an improbable hypothesis. The oldest known sedimentary rocks (Akilia Island, southern Greenland) containing carbon of biological origin date from 3,850 million years (Ma) ago. Imagine the very simple, primitive life that first developed from a world of RNA and protocells. Current deposits of stromatolites – rocks that precipitate bicarbonate, with beautiful deposits in Australia and some recently discovered in Greenland (3,700 Ma) – are very valuable because they contain within their silicified parts the oldest known fossils of microorganisms, cyanobacteria. Cyanobacteria began to conquer the ocean 3,700-3,200 Ma ago, when there was no atmospheric oxygen. Thanks to specific pigments, and in the presence of water, these cells developed photosynthesis more than 3,500 Ma ago, thus producing oxygen and sugar from light and carbon dioxide (CO_2). Oxygen then began diffusing beyond the aquatic environment: the composition of today's atmosphere – with 21% oxygen – dates from the Cretaceous period (~100 Ma ago).

In this ancient ocean, certain events occurred that proved crucial for living organisms and biodiversity:
(1) the emergence of a nuclear membrane and an individualized nucleus (prokaryote-eukaryote transition) around 2,200 Ma ago; (2) the capture of ambient cyanobacteria that became symbionts and cell organelles, mitochondria and plastids, with their own little DNA, around 2,100 and 1,400 Ma ago, respectively, and (3) the emergence of multicellular organisms and metazoans ~2,100 Ma ago.

An exceptional event then occurred in this ancient ocean: the emergence of sexuality – first in prokaryotes, later in eukaryotes. This would prove vital for the explosion of biodiversity. Sexual reproduction leads to genetic mixing, generating new traits and unprecedented diversity: all individuals are different. A population equipped with sexuality evolves much faster. In addition, the prevalence of sexuality encourages the development of an "arms race" between parasites and their hosts (co-evolution and molecular dialog), with genetic mixing ultimately resulting in faster "disarmament" of the parasite and sexual selection that is very different from natural selection.

The physical consequences of osmotic fluxes (water and electrolytes) in the marine environment led living organisms to develop two types of strategies: (1) in the vast majority of cases – from the first initial cell to shellfish – intracellular isosmotic regulation provided living organisms, separated from seawater by a biological membrane, with the same osmotic pressure (about 1,000 $mOsm.l^{-1}$) on the inside (intracellular, internal and extracellular media) as that of the seawater outside; (2) later on, starting with arthropods, extracellular anisosmotic regulation developed, where cellular and internal fluids are much less concentrated (3-400 $mOsm.l^{-1}$) than seawater. This enabled living organisms to leave the ocean. The perpetual drinking behavior at sea, found in bony fish for example, associated with very active mechanisms of electrolyte excretion through gills, constantly leads to a delicate compromise between developing maximum gill surface for capturing oxygen in a poor and highly variable environment and, on the other hand, minimum gill surface to avoid serious hydro-mineral imbalances.

Much later, during the Triassic period (~210 Ma ago), after the third major mass extinction around 251 Ma ago, the beginnings of thermoregulation developed and found their optimal efficiency among large dinosaurs, then in birds and mammals. Today 12 phyla are exclusively marine animals and have never left the ocean (echinoderms, brachiopods, chaetognaths, etc.). Furthermore, biomass can be considerable in the sea: the bacteria in the ocean subsurface layer alone accounts for over 10% of all carbon biomass on the planet. The marine environment has therefore played a key role in the history of life, and the ocean today still has a crucial role in life and climate evolution.

PARTICULARITIES OF MARINE BIODIVERSITY

Marine biodiversity is very special. The recognized species diversity in the oceans does not exceed 13% of all living species currently described - fewer than 280,000. This is very little, for two reasons. Firstly, our knowledge, especially about deep zones and microorganisms, various bacteria and protists is still very partial, so we significantly underestimate oceanic biodiversity. New techniques, such as coupling flow cytometry with molecular probes, are allowing us to discover extraordinary biological diversity. At present, the "random genome sequencing" of ocean water masses (C. Venter, sequencing of all the DNA in a volume of filtered seawater) provides scientists with data that appear to be mostly unknown. Since 2015, the circumnavigation of the world oceans carried out during the Tara Oceans expedition has produced valuable information on the abundance and variety of viruses, bacteria and protists, in particular dinoflagellates. Protists alone may account for almost one million species.

Molecular approaches (sequencing of 16S or 18S ribosomal RNA, among others) applied to all prokaryotes and very small eukaryotes generate remarkable new knowledge every day. Secondly, it is clear that marine ecosystems and species living in a continuous medium, through gamete dispersal and larval stages, are less predisposed to strict endemism than in terrestrial habitats. There are many more obstacles and isolates contributing to speciation (the evolutionary process by which new living species appear) on land than at sea. This results in significant differences in species diversity: marine ecological niches offshore do not approach the richness of land niches, which are much more fragmented and encourage greater speciation. The stability of the open ocean, at least for the past 100 million years, is quite extraordinary: small changes in pH, osmotic pressure and salinity, temperature, hydrostatic pressures associated with depth, dissolved gas content, etc. Human activities are changing all this, and we will discuss this later. This stability generates fewer new species.

In contrast, marine biomass can be considerable: the performance of phytoplankton alone (in its ability to renew itself) can account for more than 50% of the planet's total productivity. Today, there are 5 to 7 times more identified taxa on land than at sea. We can, of course, wonder about this, since initially life was exclusively marine before organisms left the ocean, several times in different places and different forms (~440 Ma ago for complex metazoans). The major Permian-Triassic mass extinction (~251 Ma ago) played a key role, with an extinction rate of 96%, both on land and at sea. The explosion of flowering plant species, insects, and many other groups on Earth around 130-110 Ma ago was decisive after the initial radiations (process in which organisms diversify rapidly from an ancestral species) beginning in the Devonian and especially the Carboniferous period.

Co-evolution between plants and pollinators, and the appearance of an infinite number of new niches have often been put forward to explain the accelerated speciation in continental environments during this period. It is also clear that the dispersal of sexual products and larvae in the ocean plays a significant role in current species distribution and biogeography. Endemism is much more limited in the open sea, due to the stability and continuity of this enormous environment. On land, species often live on only a few km², but there are no known examples of marine species with such limitations. The huge variety of marine reproduction modes also takes advantage of dispersal phenomena in water masses: males and females do not need to be close to reproduce! Thus, connectivity and many small variations in environmental factors create the great stability of the open ocean, and the very specific characteristics of the marine biodiversity it hosts. In contrast, coastal and intermediate systems with strong terrigenous influences, are subject to much greater variations.

Finally, let's not forget that biodiversity is much more than just species diversity, including both the species and their relative abundance. The meaning of the word "biodiversity" has been variously explained, but overall it expresses "the genetic information contained in each basic diversity unit, whether of an individual, a species or a population". This determines its history, past, present and future. What's more, this history is determined by processes that are themselves biodiversity components. In fact, today, we group together various approaches under this term: (1) the basic biological mechanisms explaining species diversity and characteristics, and leading us to further investigate speciation and evolution mechanisms; (2) more recent, promising approaches in functional ecology and bio-complexity, including the study of matter and energy flows, and major bio-geochemical cycles; (3) research on natural resources considered "useful" to humanity, providing food, or highly valuable substances for medicines, cosmetics, molecular probes, or ancient and innovative models for academic and applied research in order to find answers to agronomic and biomedical issues; and finally (4) the implementation of conservation strategies to preserve and maintain our planet's natural heritage, which is the birthright of future generations.

Humans have been fishing in this biodiversity since ancient times, probably for tens of thousands of years. As soon as they reached coasts, humans started collecting seafood, algae, and catching fish. Just as we farm on land, we have been raising certain marine species along the coastlines for at least 4,000 years (Egypt, China, etc.). The exploitation of renewable, living aquatic resources is booming, but there are serious concerns about its sustainability. The latest figures available from the FAO in 2013 (for the year 2012) indicate 79.9 million tonnes (Mt) for marine fisheries, 11.5 Mt for continental fisheries, 19 Mt for algae (including only 1 Mt for harvesting at sea), and 65.6 Mt for aquaculture (including 20.3 Mt at sea). This makes a grand total – for all groups and all aquatic environments – of about 176 Mt. As a result of the global warming of ocean water masses, fish stocks move on average 72 km northwards every 10 years in the northern hemisphere. Global overfishing is now a matter of great concern: 50-90% of all large pelagic fish have been caught over the past 15 years! Three quarters of all marine stocks have been fully exploited and 31% overexploited. Aquaculture is growing rapidly, but still raises questions of environmental impacts, species transplantations and, for some types of activities, the use of animal protein to feed carnivorous species of interest. The ocean is not only these living resources. There are also about 26,000 molecules of pharmacological (anti-cancer agents, antibiotics, immunosuppressant drugs, growth promoters, molecular probes, etc.) or cosmetic interest, and some extremely relevant models for scientific research, with potential biomedical and agricultural applications.

For example, phagocytosis and key molecules of carcinogenesis have been discovered thanks to sea urchins and sea stars, the molecular basis of memory thanks to a sea slug, the transmission of nerve impulses thanks to the squid, anaphylactic shock thanks to jellyfish venom, etc. All these discoveries have earned their authors a Nobel Prize.

OCEAN & CLIMATE

The ocean and the atmosphere are closely connected and exchange energy in the form of heat and moisture. The ocean absorbs heat (93%) much more readily than ice or land surfaces, and stores energy much more efficiently. In addition, it returns heat to the atmosphere more slowly than continents and contributes to the more temperate climate of coastal areas. The ocean is thus a formidable climate regulator. Changes in energy balance between atmosphere and ocean play an important role in climate change. Ocean circulation is affected by atmospheric circulation, and surface marine currents depend on winds. Winds mix surface waters down to the thermocline, below which basic circulation forces are related to temperature and salinity, influencing water density. The ocean thus contributes to the huge amounts of energy released into the atmosphere during storm and cyclone formation, affecting both continents and human populations. Upwellings – cold, nutrient-rich water masses coming up from the depths near the coasts – profoundly alter coastal climate. Taking into account their fluctuations is essential for understanding the climate system. The first three meters of the ocean surface alone store as much energy as the entire atmosphere. Moreover, the ocean has huge thermal inertia and dynamic capabilities. The action of redistributing water masses by carrying warm water from the tropics to the poles (and vice versa) is fundamental. The deep ocean plays a significant role in storing and releasing heat. In fact, this huge heat reservoir gives the ocean a crucial role in moderating climate variations. It also controls the formation of wind and rain.

The ocean traps and stores CO_2 (26-30%), thereby preventing an extreme atmospheric greenhouse effect. However, as a result, it acidifies due to the production of carbonic acid. It is now 30% more acidic than 250 years ago. Oceanic phytoplankton also stores CO_2 in the surface layer, as do all the biocalcifiers. Ocean circulation redistributes heat and salinity – both important factors in controlling the climate machine. Currents along the eastern and western borders of the continents are critical, and past fluctuations led to the alternation of glacial and temperate periods.

The ocean thus plays an essential role in climate regulation, but biodiversity loss and pollution also affect it and create conditions for climate change. The amount of carbon dioxide in the atmosphere and the ocean is increasing. Average temperatures of the lower atmospheric layer and of the ocean surface are rising. Moreover, mean sea levels are rising three times faster than 50 years ago. Rapid changes in seawater chemical composition have a harmful impact on ocean ecosystems, already stressed by overfishing and pollution. This massive and widespread pollution affects all parts of the world, because humans have managed to contaminate areas where they do not even live (including the Arctic ice pack and Antarctica)! Plastic microparticles, carried by ocean gyres, have accumulated in huge concentrations in five areas of the world ocean. No contaminated effluents should reach the sea ever again! Only a healthy ocean can fulfill all these functions.

Climate change has a direct role in biological diversity loss, and, in turn, this loss contributes to the very problem!

Moreover, let's not forget that the impacts of rapid climate change are compounded by other severe problems: destruction and pollution of coastlines, accelerating systematic overexploitation of living resources, and the uncontrolled spread of species (including in the ballast water of large ships). It is also very important to better legislate and regulate actions before allowing deep sea mineral exploration and mining, as the deep ocean is particularly fragile (and is stable in the very long term).

That is a lot for the ocean to handle and it is high time to take action!

Exploited marine biodiversity and climate change

Philippe Cury

Climate change is impacting the productivity of marine ecosystems and fisheries, while demand for fish for human consumption is increasing. Fish is the main source of animal protein for one billion people and is one of the most traded renewable resources in the world. Changes in physical and chemical characteristics of seawater affect individual metabolism, species' life cycles, predator-prey relationships, and changes in habitat. Geographic distributions of fish (migration rate towards the poles is 72.0 ± 13.5 km/decade) and ecosystem dynamics could undergo profound disruption in the coming decades, impacting fisheries globally and jeopardizing food security in many southern countries. Maintaining healthy, productive marine ecosystems is a critical issue.

CHALLENGES FACING MARINE FISHERIES

Climate change is affecting marine ecosystem productivity and impacting fisheries. This sector represents the last human activity exploiting, on an industrial scale, a wild resource that is sensitive to environmental fluctuations. Population growth and changes in eating habits have led to increasing demand for fish for human consumption. Fish is now the main source of animal protein for one billion people worldwide. It is also one of the most traded global renewable resources: 28 million tonnes of marine fish are destined for US, European and Japanese markets, which together account for 35% of world catches, with over two-thirds provided from southern hemisphere countries (Swartz *et al.*, 2010).

In a context of climate change, fish geographic distribution and ecosystem dynamics are expected to undergo profound disruption in the coming decades, thus affecting fisheries worldwide, and jeopardizing food security in many countries of the southern hemisphere (Lam *et al.*, 2012).

IMPACTS OF CLIMATE CHANGE ON MARINE BIODIVERSITY

Marine life is affected by variations in water temperature, oxygen concentrations, acidification, the severity of extreme climate events and ocean biogeochemical properties. These changes have either direct or indirect effects on individual metabolism (growth, respiration, etc.), species' life cycles, predator-prey relationships and changes in habitat.

They affect both the individual level, and the interactions between species and habitats, thus triggering changes in species assemblages, but also in productivity and ecosystem resilience (Goulletquer *et al.*, 2013).

Disturbances are now clearly established across a wide variety of taxonomic groups, ranging from plankton to top predators, and are in line with theoretical approaches to the impact of climate change (Poloczanska, 2014). Beaugrand *et al.* already demonstrated in 2002 that large-scale changes were occurring in the biogeography of calanoid crustaceans in the northeast Atlantic Ocean and European continental seas. Northward shifts of warm-water species by more than 10° latitude coinciding with a decrease in the number of cold-water species are related both to the rise in temperature in the northern hemisphere and to the North Atlantic Oscillation.

Results from a recent global analysis show that changes in phenology, distribution and abundance are overwhelmingly (81%) in line with the expected responses in a context of climate change (Poloczanska, 2013). Today, a large number of biological events concerning maximal phytoplankton and zooplankton abundance, as well as reproduction and migration of invertebrates, fish and seabirds, all take place earlier in the year. Hence, over the past fifty years, spring events have been shifting earlier for many species by an average of 4.4 ± 0.7 days per decade, and summer events by 4.4 ± 1.1 days per decade. Observations show that for all taxonomic groups, albeit with great heterogeneity, the migration rate towards the poles reaches 72.0 ± 13.5 kilometers per decade. Changes in distribution of benthic, pelagic and demersal species can extend up to a thousand kilometers.

These poleward migrations have led to an increase in the number of warm-water species in areas like the Bering Sea, the Barents Sea and the North Sea. The observed modifications in benthic fish and shellfish distribution with latitude and depth can be mainly explained by changes in sea temperature (Pinsky *et al.*, 2013). The migration rates recorded in the marine environment appear to be faster than those observed in the terrestrial environment.

IMPACT ON FISHERIES AND GLOBAL FOOD SECURITY

Marine fish and invertebrates respond to ocean warming by changing their distribution areas, usually shifting to higher latitudes and deeper waters (Cheung *et al.*, 2009). The variation in the global catch potential for 1,066 species of marine fish and invertebrates harvested between 2005 and 2055 can be predicted based on different climate change scenarios. According to these studies (Cheung *et al.*, 2009), climate change may cause a large-scale redistribution of the total catch potential, with an average increase of 30 to 70% in high-latitude regions and a decrease of up to 40% in the tropical regions. Among the 20 most important fishing areas of the Exclusive Economic Zone (EEZ) in terms of landings, the EEZ regions with the highest increase in catch potential by 2055 are Norway, Greenland, the United States (Alaska) and Russia (Asia). On the other hand, the EEZ areas with the greatest loss of maximum catch potential include Indonesia, the United States (except Alaska and Hawaii), Chile and China. Many severely affected areas are located in the tropics and are socio-economically vulnerable to these changes.

Further studies, taking into account factors other than ocean temperature, highlight the sensitivity of marine ecosystems to biogeochemical change and the need to include possible hypotheses concerning their biological and ecological effects in impact assessments (Cheung *et al.*, 2011).

Hence, the predictions for the year 2050 regarding the distribution and catch potential of 120 fish and demersal invertebrate species harvested in the North Atlantic show that ocean acidification and decreasing oxygen concentrations could reduce growth performance and lower the estimated catch potential by 20 to 30% (10-year average for 2050 compared to 2005) in comparison with simulations that do not take these disrupting factors into account. In addition, changes in the phytoplankton community structure could also reduce the predicted catch potential by about 10%. All these results highlight the sensitivity of marine ecosystems to biogeochemical changes (Cheung *et al.*, 2011). The observed changes in the species composition of catches between 1970 and 2006 are largely attributable to long-term ocean warming (Cheung *et al.*, 2013). Modifications in the marine environment are expected to continue to generate considerable challenges and costs for human societies worldwide, particularly for developing countries (Hoegh-Guldberg & Bruno, 2010).

HOW CAN WE LIMIT THE IMPACTS OF CLIMATE CHANGE ON MARINE ECOSYSTEMS?

The best way to combat the effects of climate change is to preserve biodiversity and avoid overexploiting certain species. The latter has been recognized as a factor aggravating the impacts of climate change (Perry *et al.*, 2010). The Ecosystem Approach to Fisheries (EAF) reconciles the exploitation and conservation of species, *i.e.* it aims to maintain ecosystem integrity and resilience. The EAF thus contributes to the crucial issue of keeping marine ecosystems healthy and productive, while proposing a new way of considering fish exploitation in a broader context (www.fao.org/fishery/eaf-net).

The role played by Marine Protected Areas (MPAs) in protecting marine habitats and biodiversity, thereby making ecosystems more resilient, is crucial to support efforts to mitigate climate change (Roberts *et al.*, 2017). The need to develop an adaptation policy designed to minimize the impacts of climate change through fishing must become a priority. This will require better anticipation of changes using predictive scenarios (in the sense of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services – IPBES) and implementing public policies to be able to adapt to the changes taking place in marine ecosystems within the framework of the UN 2030 Agenda for Sustainable Development (Euzen *et al.*, 2017). Although the impact of climate change will most of the time remain unavoidable, the adaptation of communities to rapid changes has yet to be understood and assessed, which opens up many opportunities for research on this topic.

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Overfishing and sustainable fishing: challenges for today and tomorrow

Didier Gascuel

During the 20th century, humans increasingly exploited the living resources of the ocean. The increase in catches was accompanied by a decrease in resources and overfishing became a widespread practice, characterized by inefficiency of the production system. In Europe, however, fishing pressure has been declining for about 15 years, and there are initial signs of recovery of exploited stocks. But to ensure sustainable fishing, it is not enough to adjust catches to the biological production of each stock. This is of particular importance given that the ecosystem approach to fisheries and the expected impacts of climate change require us to tighten up environmental requirements and rethink the concept of sustainable fisheries.

EXPLOITING THE OCEANS

People have been sea fishing for thousands of years and the first impacts are long-standing. Centuries ago, the most fragile species, marine mammals, some selachians, migratory species such as sturgeon, or shellfish beds may already have been severely affected by fishing. However, for a very long time, this activity was limited to coastal resources and a small number of carefully selected species. Vast areas of the oceans and many species have long remained unaffected by humans. At the end of the 19th century, the ocean still appeared immense, and scientists concluded that marine resources were limitless.

It was not until the 20th century that humans truly began to exploit living marine resources on a global scale. The trend, which started at the end of the previous century with the development of engines and trawls, intensified after World War II, when large industrial fishing fleets developed and gradually conquered the world's oceans (Fig. 1). Within a few decades, the total capacity of vessels increased tenfold (Bell *et al.*, 2016), and production fivefold (FAO 2018 and 2019). Production peaked in 1996, with global reported catches of 87 million tonnes (source: FAO). This figure could even be as much as 130 million tonnes if discards and illegal, unreported or unregulated (IUU) catches are taken into account (source: SAUP; Pauly & Zeller, 2015).

Since then, catch has declined sharply, mainly due to the overfishing of many stocks. The resulting loss is estimated at more than one million tonnes every year.

The increased fish catch was accompanied by a sharp fall in the abundance of exploited stocks. Several studies estimate that the biomass of large bottom feeders and some pelagic predators declined by a factor of 5 to 10 over the 20th century (Christensen *et al.*, 2003, Worm *et al.*, 2009; Juan-Jordà *et al.*, 2011). In a report based on the analysis of 1,135 fisheries, Costello *et al.* (2008) showed that the biomass of 27% of the global fish stocks has been reduced at least tenfold, including 9% whose biomass declined by a factor of 100 or more. Conversely, some species of forage fish, as well as many mollusks or crustaceans, may have benefited from a release in predation linked to the overexploitation of their predators. In the end, partly compensating for this, the total biomass of exploitable species is estimated to have declined by a factor of 2 to 2.5 on a global scale, with obvious repercussions on all food webs and marine ecosystem functioning (Gascuel *et al.*, 2019).

OVERFISHING IS NOT WHAT YOU THINK IT IS

The general public often confuses sustainability and balance, believing that nature provides us every year with a given production that we can exploit without impact. A cornucopia to satisfy our appetite. Overfishing would therefore be the equivalent of bulimia, leading us to "harvest more than the stock produces". In fact, that is not how things work. In

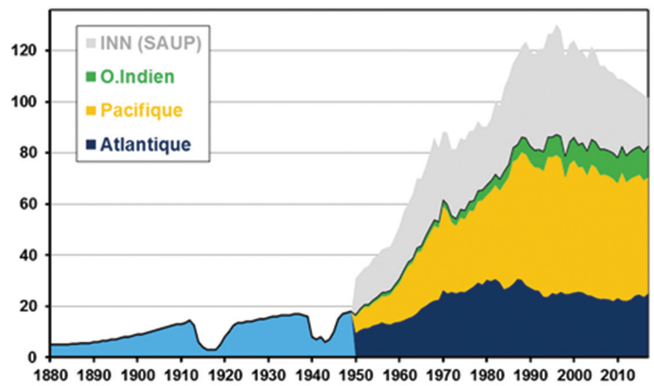

Fig.1 — Trend between 1880 and 2017 in global marine fisheries production (excluding algae), in millions of tonnes. 1880-1949: empirical reconstruction from the scientific literature. 1950-2017: data from FAO (2019) and the Sea Around Us Project (SAUP) regarding illegal, unreported and unregulated fisheries (IUU).

the absence of fishing, the net biological production of a natural population is theoretically zero. Natural mortality only just offsets the biomass gains associated with individual reproduction or growth, and the population adjusts to the carrying capacity of the environment. Inevitably, the first fisherman therefore catches more than the stock produces. This necessarily impacts the resource whose biomass decreases until the resulting reduction in intraspecific competition compensates for the increase in fishing pressure. If the latter does not increase again, then a new steady state is established.

"I am fishing more than the stock produces" is therefore only a transitional situation between two states of the stock, evolving towards a lower balance than the previous one, but which does not necessarily reflect overfishing. In contrast, a very low biomass stock, which also has low biological production, can be maintained in such an undesirable state. To this end, humans just need not to fish more than the stock produces. A balanced overfishing situation will then be maintained (at least in the medium term), regardless of possible ecosystem changes or genetic drifts. In fact, stock extinction is the ultimate case of perfect balance, in which it is a certainty that no fish will be caught – in other words, "no more than the stock produces". Everyone will agree that this is not a sound fishery management strategy!

Overfishing, therefore, has nothing to do with imbalance. It reflects a very specific situation in the fisheries sector. In any other sector, it is accepted that when the means of production increase, production also increases. More capital and labor invested leads to a growing production function. More workers and machine tools manufacture more cars.

In some areas, such as agriculture, it is accepted that production can reach an asymptotic value. More tractors in a field do not increase production indefinitely. In fisheries, the dynamics are different. Above a certain threshold, when the means of production increase, production decreases. An increase in the number of larger, more efficient vessels, equipped with more innovative electronic devices (fisheries scientists speak of increased fishing effort or pressure) leads to lower catches. The fundamental reason is that the natural resource is affected. Fish catch declines because the ecological impact is too high, because the ecological capital is affected beyond what is "reasonable".

The concept of overfishing refers to these situations of decreasing production function. In fact, it characterizes a production system that has "gone mad", a situation in which we spend more, work more, consume more diesel, etc. but fish less. It is as if, in the automotive industry, the machine tools that build cars were being supplemented with other expensive tools designed to destroy part of the production.

At the same time as fishermen catch fish, they also destroy the stock that could have been caught the next day! In other words, overfishing refers to a strange situation where fishermen must be persuaded to stay home some of the time so that stocks can replenish. Ultimately, this would actually result in higher annual catches.

Basically, overfisching situations therefore reflect the inefficiency of the production system. Fishermen are at the same time the most direct contributors and victims, as they are impacted by the low economic profitability of fisheries and fluctuating catches. Of course, the resource is also affected, with low biomass and the truncation of demographic structures. Undoubtedly, these situations should be avoided. Although the "how" is still the subject of debate, all stakeholders in the fisheries sector agree on this principle.

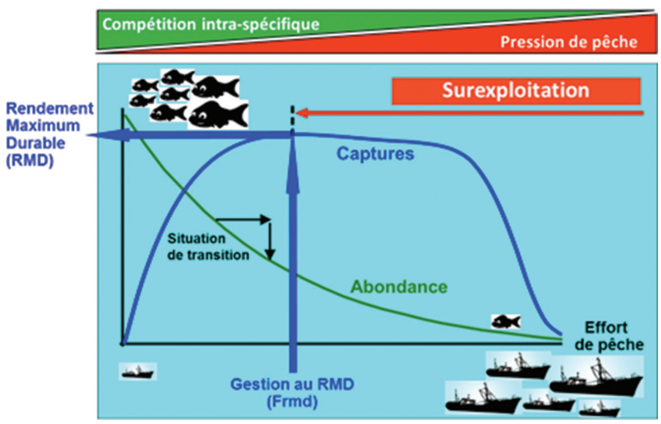

Fig.2 — Conceptual diagram of how the abundance of an exploited stock and the resulting catch evolve, for an increasing fishing effort (equilibrium curves). Concept of overfishing and principle of Maximum Sustainable Yield (MSY) management.

As early as the 1930s, the first fisheries biologists identified the risk of overexploitation and called for a limitation of fishing effort. This idea was developed after the war, when the US government took the initiative to propose "Maximum Sustainable Yield (MSY) management" as an international standard for sound fisheries management. This standard was formally adopted by the United Nations in 1955 and enshrined in the 1982 UN Convention on the Law of the Sea (UNCLOS). For each exploited stock, the objective is to set the fishing effort at a level that allows maximum catch, as a long-term average value. Neither too few vessels, which would catch few fish, nor too many, which would leave insufficient residual biomass in the sea to sustain high catch rates. MSY management therefore ensures – just barely – that there is no overfishing.

SUSTAINABLE FISHERIES, WHERE DO WE STAND?

It is now customary to refer to any situation in which the stock is not overexploited as "sustainable fishery" – in particular situations in which MSY management objectives are achieved. Contrary to what the general public often believes, sustainable fishery is not defined by an objective of balanced management preserving the resource, but by an objective of maximizing long-term catches for each stock exploited.

To achieve this goal, governments worldwide have gradually implemented measures to limit fishing effort. For large ocean stocks, accounting for most of the fish catch and often shared between different countries and fisheries, decades of experience have shown that the most effective method is to directly limit catches by introducing fishing quotas. UNCLOS has been adapted to reflect this reality, giving nations very extensive fisheries policing powers within their Exclusive Economic Zones (*i.e.* up to 200 nautical miles or about 360 km from their coastline). Since the 1980s, major developed countries have adopted increasingly restrictive quota policies. Unquestionable success has been achieved for some stocks, particularly in the USA, Australia, and Europe. Nonetheless, these successes have not been enough to prevent a dramatic rise in the global fishing effort and the multiplication of overfishing situations in most of the world's oceans.

FAO assessments (2018) show that 33% of the global stocks subject to scientific evaluation are now overexploited. Unfortunately, this figure is steadily increasing, with fishing pressure continuing to rise significantly, mainly in Asia. Other analyses provide an even more pessimistic picture. For example, Costello *et al.* (2016) estimate that, based on data from 4,713 fisheries worldwide (representing 78% of global reported fish catch), 68% of stocks are now overexploited or at biomass levels too low to fulfill MSY. The median value of fishing pressure is estimated to be equal to 1.5 times the target value and biomass is only 78% of the target objective.

Europe has long been the black sheep among developed countries. Due to a lack of shared political will in a political space under construction, fishing pressure increased until the late 1990s.

It is estimated that nearly 90% of Europe's major stocks were then overexploited, with a mean annual harvest rate of about 45% of the biomass present (Gascuel *et al.*, 2016). Fishing quotas only began to become truly restrictive in 1998, and the standard for maximum sustainable yield management was only formally adopted in 2005. Within a few years, however, the measures taken, and tighter control mechanisms have resulted in a real trend reversal. The latest available assessments (STECF, 2019) show that the harvest rate has been almost halved in the European waters of the North-East Atlantic. On average, it is now close to the MSY management objective (Fig. 3).

In parallel, the average biomass of the stocks assessed in this area is estimated to have increased by 40% for the best-known stocks, probably even more according to the partial data available on a wider scale. However, abundances were initially extremely low, and are still low, well below the level that will produce the maximum sustainable yield. Moreover, average values hide large disparities. The latest tally shows that 41% of the relevant stocks are still being overexploited in European waters of the Atlantic (STECF, 2019). Above all, there are no signs of improvement in the Mediterranean Sea, where only the iconic stock of bluefin tuna is subject to quotas. The fishing situation in Europe therefore remains fragile. Recent developments have, however, highlighted that effective action can be taken to reduce fishing pressure, thus allowing stocks to replenish. This is positive news. Providing the political will is there, we are not condemned to an inexorable decline in global fish stocks and widespread overfishing. Fish stocks can recover and be healthy again.

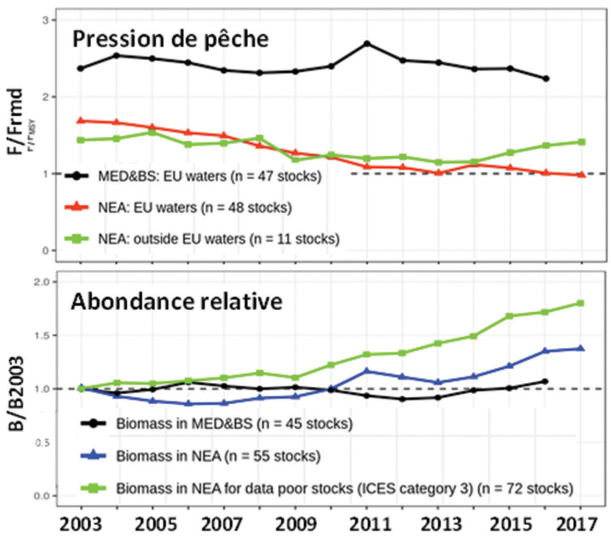

Fig.3 — Trend in fishing pressure indicators and average abundance of the stocks exploited in Europe (STECF, 2019). The indicators are calculated for all the stocks assessed by the International Council for the Exploration of the Sea (ICES). Top: The relative value of fishing pressure in relation to the MSY management objective (in the Mediterranean and the Black Sea, and in European or non-European waters of the North-East Atlantic). Bottom: Mean relative abundance compared with 2003 (in the Mediterranean, the Black Sea, and in the North-East Atlantic for well-known and data-poor stocks).

ECOSYSTEM APPROACH AND CLIMATE CHANGE: HOW DO WE ENHANCE RESILIENCE?

An essential question remains: is the progress made commensurate with the current challenges? Assuming that the MSY management standard will apply everywhere and lead to the expected stock replenishment (which is far from certain), does it really ensure long-term sustainable fisheries? There are two main considerations that raise doubts and prompt us to revisit the question of management standards.

First of all, it should be emphasized that the approach currently being implemented, in particular in Europe, was based mainly on mental representations and models developed more than fifty years ago, in the context of a monospecific approach. Implicitly, this approach assumes that managing each stock separately, according to the MSY standard, leads to a globally sustainable fishery, as if stocks did not interact with each other and all ecosystem compartments; and as if the biomass reduction imposed on every living organism had no impact on their prey, competitors or predators, and no chain effects on the entire structure and functioning of food webs. Over time, it has gradually been accepted that a broader approach, referred to as the ecosystem approach to fisheries, must be implemented (Garcia, 2003; Cury & Gascuel, 2017). This approach requires all impacts to be taken into account: those affecting each ecosystem compartment, but also food webs or habitats, and more generally, the productivity, stability, and resilience characteristics of ecosystems. There is little doubt that reducing the direct impact on each exploited stock is a major challenge in lessening the overall impact on ecosystems.

In other words, maximizing long-term catch is not enough. Paradoxically, the ecosystem approach invites us to rethink sustainable fisheries by studying the old model, and especially the curve that measures the impact of exploitation on the biomass of each exploited stock. It should be noted here that, in the absence of specific measures to protect juveniles, the MSY standard leads to a two-and-a-half to threefold reduction in the abundance of the stock in question, compared with a situation with no fishing activities. Who could guarantee that such an impact, repeated on each stock, is truly sustainable? This is all the more important since the introduction of selectivity measures would help maintain high fish catch while limiting biomass reduction. By catching only the largest fish, production could be maintained and the residual biomass left in the water could be increased substantially (Froese *et al.*, 2016).

The second major reason to rethink the management standard is climate change. This is known to have very significant impacts, not only on species distribution, but also on the productivity and stability of marine ecosystems (Cheung *et al.*, 2010; Gascuel, 2019), and these will undoubtedly increase in the future. Here, too, an upward revision of all resource protection measures is an obvious necessity. Reducing the impact of fishing, allowing resources to replenish and, more generally, ecosystems to become healthy again appears to be the best possible adaptation to the expected impacts of climate change. High biomass levels, in particular, ensure greater functional diversity, and therefore greater ecosystem resilience. Moreover, modeling shows that foregoing catch maximization, by accepting slightly lower catches, would have a double advantage.

On the one hand, reducing the generated impact would significantly improve ecosystem functioning and stability (Worm *et al.*, 2009). On the other hand, reducing fishing costs would largely offset catch loss, and thus contribute to improving the profitability of fishing (Gordon, 1954). Objectives of economic optimization or ecological resilience thus lead to accepting a situation of significant under-exploitation.

At international level, MSY management remains today the standard for sound fisheries management. Many nations still follow this standard. Europe is gradually approaching the standard performance goals, while other countries still seem a long way off, particularly in Asia or developing countries. Conversely, some countries are already going beyond this standard, adopting more cautious management standards. This is the case in the USA and Australia, for example. In the end, the situation of the different countries tells us that the concept of sustainable fisheries is not a scientific truth established once and for all. It is a social construct arising from power relations between stakeholders of the fishery sector, societal representations and values, and policy arbitration. It is a construct on which the future of the ocean depends, and which all citizens would do well to embrace.

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Aquaculture and global changes

Marc Metian

Aquaculture is a booming sector, currently supplying more than half of the fish and shellfish on world markets. Climate change will affect some aquaculture activities; however, the scale of these impacts cannot yet be quantified, given the uncertainty of global models. Adaptation of production systems is potentially feasible through actions by all stakeholders involved. Direct impacts will be related to changes in production conditions in freshwater, brackish water and marine environments. The main indirect impact is likely to be related to the dependence on an exogenous food supply for the cultivated organisms. However, the negative (inland water eutrophication, ocean acidification, etc.) and positive impacts (aquaculture activities in colder areas, better growth of farmed organisms, etc.) could balance out. Finally, impacts will vary depending on region and type of production.

Aquaculture – an ancient activity, close to agriculture, consisting of animal or plant production in aquatic environment – is currently booming. It has been growing exponentially since the 1980s and now supplies more than half of the fish and shellfish for the global market, while global fishing statistics remain stationary.

Scientists expect aquaculture to be severely impacted by climate change. Various publications on this issue[1] state that the forecast global environmental conditions will affect the aquaculture sector. It is important to note, however, that all the predicted impacts will not necessarily be negative.

In fact, climate change is likely to create development opportunities in countries or regions where current production is low.

In aquaculture, unlike fisheries, human intervention occurs throughout the life cycle, with some exceptions[2]. This therefore allows stakeholders to take action to adapt[3] to climate change. The success of the adjustments made will depend upon the severity of environmental conditions, the costs and the adaptability of the relevant actors, as well as upon national and international decision-makers.

DIRECT RISKS OF GLOBAL CHANGE FOR AQUACULTURE

In 2017, global aquaculture production reached a record level of 111.0 million tonnes (fresh weight equivalent; valued at 242.8 billion US dollars), including 79.2 million tonnes of consumables (231.0 billion US dollars) and 31.8 million tonnes of aquatic plants (mainly algae; valued at 11.8 billion US dollars). Climate change will jeopardize some aquaculture activities, but the extent of these impacts cannot yet be quantified in the absence of global models that take into account all direct and indirect effects of global changes.

1 See recommended references.
2 In particular, aquaculture activities based on individual catches from natural environments.

3 In the case of production, adaptation means finding a technical solution to sustain the activity despite constraints.

In any case, there will be consequences on production, which in turn will affect humans. The global demand for fishery and aquaculture products is increasing. Moreover, aquaculture products are an important source of nutritious food for developed and developing countries (viz. a contribution to food security), and represent a source of income for all communities, regardless of their standard of living. Among the impacts of climate change affecting aquaculture, direct consequences are expected to be mainly related to changes in production conditions. Average production will thus be affected, not only in the marine environment (Table 1), but also in inland areas (fresh and brackish waters), where the majority of global production is concentrated. These inland production areas are more sensitive to changes; in fact, global warming and the resulting temperature rise in global surface waters are expected to have a much greater impact on aquaculture in inland areas than in the marine environment (due to the modification of the optimal temperature range of the organisms currently cultivated).

Table 1. Summary of climate change impacts on oceans and coastal areas affecting aquaculture (from Allison *et al.*, 2011).

- Change in temperature
- Change in ocean salinity, density and
- stratification
- Change in ocean circulation and coastal upwellings
- Rising sea levels
- Land-ocean interactions
- Changes in natural climate variations (ENSO)
- Increasing frequency and severity of extreme weather events
- Ocean acidification and changes in seawater chemistry
- Timing and success of physiological processes, spawning and recruitment
- Primary production
- Changes in marine life distribution
- Changes in marine life abundance
- Phenomenological changes (*i.e.* life cycle stage duration)
- Species invasion and diseases
- Changes in climate regime and extreme events

Nevertheless, the negative and positive impacts could balance out. Among the positive impacts of climate change, scientific models predict an expansion of aquaculture activities towards cooler parts of the world, which are likely to have longer thawing periods, better growth rates of farmed organisms, and an improved food conversion capacity for the latter. However, these positive effects will be concurrent with negative impacts (*e.g.* increased eutrophication in inland waters and ocean acidification). In both cases (negative or positive effects), production methods need be adapted.

DIVERSE VULNERABILITIES AND DIFFERENT TYPES OF PRODUCTION

Aquaculture is not carried out uniformly throughout the world. This heterogeneity must be taken into account to establish a meaningful assessment of the potential impacts of climate change. Climate change is likely to occur with differing intensities depending on the geographical area, thus resulting in different impacts. It is therefore necessary to keep in mind that aquaculture exists mainly in three climate regimes[4] (tropical, subtropical and temperate), in three types of environment (seawater, freshwater and brackish water), and covers a wide range of taxa.

In Asia, impacts related solely to global warming are likely to be essentially beneficial, resulting in better growth rates of farmed stocks. However, this should not conceal the impacts of climate change on water availability, worsening weather conditions, such as extreme rainfall, increasing eutrophication and stratification of stagnant water.

The concentration of aquaculture in certain areas (namely Asia and the tropics) makes it possible to focus on developing adaptation strategies to locally

4 Aquaculture is predominant in tropical and subtropical regions and is mainly located in Asia.

mitigate the impacts of climate change, especially if the expected gap between supply and demand for aquatic products for consumption is to be filled by aquaculture.

Among the various global changes predicted, one in particular is regularly highlighted, as shellfish production on the west coast of the United States is already experiencing its impacts: ocean acidification. The associated adverse effects are well documented for two key product groups in aquaculture: bivalves and crustaceans.

The increased concentration of dissolved CO_2 in seawater can impact marine life at three levels: (1) the limitation of available carbonates, mainly affecting calcifying organisms; (2) the increase in H^+ ions in the water resulting in decreasing pH – *i.e.* acidification of surrounding environment; and (3) an increase in CO_2 partial pressure in organisms, causing hypercapnia.

The socio-economic impact will be significant, particularly on shellfish production. In 2017, although farmed shellfish only accounted for a volume of 7% (8.4 million tonnes) of the total aquaculture production for human consumption, it represented a value of 25% (61.1 billion U.S. dollars). In contrast, mollusk production (17.4 million tonnes), although more than twice that of crustaceans only represented half of their economic value. There have been attempts to adapt to the impacts of climate change on different production systems, including the use of cages or closed systems.

Example: What will the impacts of climate change be on the Chinese aquaculture industry?

In terms of risks, the latest IPCC forecasts for East Asia are:

- Average annual temperature: +3.3°C by 2100;
- A possible increase in total annual precipitation;
- Increased climate variability.

According to several authors, the negative impacts related to fish production will be: heat stress, increased oxygen demand, increased pollutant toxicity and a higher incidence of fish diseases. More generally, production systems are likely to undergo a decrease in oxygen solubility in a warmed ocean, eutrophication, stratification, uncertain water supply, and saltwater incursion inland due to rising sea levels.

INDIRECT RISKS OF GLOBAL CHANGE FOR AQUACULTURE

The impacts of climate change are not just limited to the surrounding environment of the production site. The predicted conditions will foster, in particular, the remobilization of contaminants that are currently not bioavailable, the emergence of diseases, increased toxic algal blooms, the disappearance of key species (*e.g.*, phytoplankton for filter feeders) or conversely, the occurrence of harmful species in the culture medium.

However, the main indirect impact of climate change on aquaculture is likely to be linked to its dependence on external food supplies. Indeed, 70% of the world's aquaculture production depends on the supply and production of raw materials from agriculture and industrial fisheries. These external inputs will be affected by climate change and will therefore have an indirect impact on the aquaculture industry.

The negative impacts are likely to be experienced most sharply in the temperate regions, where fish farming is entirely based on carnivorous species. However, other areas are also expected to be affected, as the vast majority of countries involved in aquaculture production use fishmeal.

Recent changes in the distribution and productivity of a number of fish species can be linked with a degree of certainty to regional climate variability, such as the El Nino-Southern Oscillation. There is a strong relationship between fishing and climate trends. Moreover, the increased frequency and intensity of extreme weather events are likely to have a major impact on fisheries production, and therefore indirectly on aquaculture.

As the indirect impacts on aquaculture activities and/or productivity are subtle, complex and difficult to identify, it is challenging to develop measures to adapt to climate change. A close and interdependent relationship exists between fisheries and aquaculture. This relationship is illustrated by the contribution of some inputs derived from the fisheries industry and used in aquaculture, including fishmeal, fish oils and, to a lesser extent, juvenile organisms. The impacts of climate change on fisheries worldwide will therefore have consequences on the aquaculture industry.

CONCLUSION AND RECOMMENDATIONS

There are, or will be, solutions to help aquaculture adapt to climate change. The resilience of aquaculture sensus *lato to* unexpected shocks has already been proven. In particular, this can be illustrated by the short time it took for most Asian countries to replace shrimp species when one species had been severely affected by a virus (with a regionally significant dispersion) or by the speed at which some countries affected by devastating weather events resumed normal production.

Despite these advantages, the aquaculture sector must prepare itself. Advances in the development of predictive models must be made, taking into account the multiple stress factors that will result from climate change. Moreover, progress in the selection of species better adapted to cope with the predicted conditions (multiple stressors) is needed, along with a conceptualization of adaptation solutions for cultivation practices.

Additionally, it is important that the changes in aquaculture practices be as environmentally friendly as possible, including the efficient use of resources such as water, land, energy and nutrients in agricultural systems. Feed formulation improvements are in progress and will have to be made, and should ideally include ingredients derived from alternative marine resources (such as by-products from fish filleting factories). More environmentally friendly aquaculture could also benefit from the implementation of certification programs. Even though these programs do exist, the concept of sustainable aquaculture is still the subject of debate.

However, the current situation is not as bad as what is reported in the media. Even though the current production practices are far from perfect, they are generally more efficient, in terms of both energy and product produced per unit of food input than other land-based animal production systems. Furthermore, aquaculture is relatively less environmentally damaging than most agricultural counterparts.

These conclusions are almost always based on high-value aquaculture products, such as shrimps and carnivorous fish like salmon, hence leading to false ideas among the general public, planners, developers and investors. In reality, the vast majority of aquaculture still depends on fish and shellfish situated at the bottom of the food chain. Moreover, macroalgae are also produced and can potentially act as carbon sinks, thus contributing to carbon sequestration.

Finally, although many uncertainties remain concerning the magnitude of climate change impacts on aquaculture and the sector's adaptability, aquaculture will undoubtedly be affected. Action must therefore be preventively taken to allow the continuation of this activity upon which the world's population is becoming increasingly dependent.

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The Arctic: Opportunities, Concerns and Challenges

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Anne Choquet
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The Arctic is pictured in the collective mind as a white and frozen desert, with only a few polar bears, explorers and Eskimos sprinkled around. It is, however, inhabited by very diverse people, and several industries are well established in the Arctic, through the Arctic, or at the periphery of the Arctic Circle. Receding and thinning sea ice because of climate change opens up access to natural resources, shipping routes and touristic areas, thereby providing new opportunities for economic development in the Arctic. The potentially high rewards are extremely attractive, but at high financial, environmental and social costs in a high-risk environment. Some stakeholders have started securing access to Arctic resources, sowing the seeds for a 'cold rush'. Despite increased prominence in the media of Arctic bonanza, sometimes closer to myth than reality, such 'cold rush' does not seem to have fully materialised yet, slowed down by high investment costs and legal considerations, as well as high diplomatic, political and social sensitivity. The main political challenge ahead is for decision-makers to successfully reconcile highly contrasted perspectives and interests in the Arctic, from the local to the international levels, by building up existing institutional capacity at the pace of economic development. There is certainly strong potential for creating shared economic wealth and well-being, with a fair distribution of Arctic benefits. Choices for economic development, coordination and cooperation by Arctic countries and private actors in the next few years will shape the Arctic of tomorrow.

The Arctic refers to an oceanic area around the North Pole and Arctic Circle, partly covered in sea ice and surrounded by frozen lands. There is no agreed delineation of an 'Arctic Region' and population estimates vary from 4 to 10 million depending on the geographic extent considered (Ahlenius *et al.*, 2005, p.6 & 14; Duhaime and Caron, 2006; Norway Ministry for Foreign Affairs, 2015, p.5). The Arctic can refer to two zones: the Arctic Ocean and the Arctic region. The Arctic Ocean is bordered by five sovereign states (United States of America, Canada, Denmark, Norway, and the Russian Federation). The Arctic region is broader and encompasses all states with land in the Arctic Circle. The Arctic region includes all five states bordering the Arctic Ocean, with the addition of Iceland, Finland and Sweden.

The Arctic is part of the global climate system with heat redistribution through ocean currents between the North Pole and the equator, as well as heat and nutrient redistribution between surface waters and the deep abyssal plains (Ocean & Climate, 2015). Impacts from climate change in the Arctic are stronger and faster than any other areas of the globe. In addition to being sensitive to outside impacts, Arctic emissions and pollutions have a greater impact on the Arctic itself (Crate, 2012). The Arctic is therefore seen as the 'canary in the mine', an early warning sentinel of climate change impacts to come (The Arctic – The Canary in the Mine. Global implications of Arctic climate change. Norwegian-French conference in Paris, 17 March 2015; Dahl, 2015).

The Arctic sea ice is now shrinking and thinning because of rising concentrations of anthropogenic greenhouse gases in the atmosphere, leaving longer sea ice-free seasons (Serreze *et al.*, 2007; Boé *et al.*, 2009; Kwok and Rothrock, 2009; Parkinson, 2014; Speich *et al.*, 2015; US National Snow and Ice Data Center in Boulder Colorado, 03 March 2015). Scientific scenarios and models have shown that sea level could drop slightly in some areas of the Arctic and increase by more than 70 cm along the east coast of the United States (Ocean & Climate, 2015).

Such changes in the Arctic open up access to Arctic ocean-floor resources and sea routes, with new opportunities for economic development in the region, which could impact global trade patterns and trends (Valsson and Ulfarsson, 2011). However, infrastructures remain very costly, and sparse and isolated populations do not necessarily have the capacity to combine their strengths to overcome common weaknesses and threats (Heininen and Exner-Pirot, 2018).

If left open and uncoordinated, economic development of the Arctic could drive to a wild 'cold rush' driven by selfish interests rather than a concerted effort to make the most of these new opportunities for society as a whole, through win-win solutions that create shared wealth and well-being for all.

- What potential economic benefits would we derive from economic development of activities in the Arctic, and at what costs?
- What potential environmental and social consequences for such economic development?
- Have there been any signs of a 'cold rush' materialising yet?
- What are the political challenges ahead if we are to make the most of the economic opportunities opening up in the Arctic?

THE ARCTIC, A PLACE OF INTENSE ECONOMIC ACTIVITY BUT WITH WIDE VARIATIONS BETWEEN COUNTRIES AND INDUSTRIES

There are several industries already operating in the Arctic, through the Arctic, or at the periphery of the Arctic Circle. These include fishing and forestry, mining (oil, gas, minerals), shipping (sea transport), manufacturing (fish processing, electronics), Arctic tourism, and other services associated with human settlements such as education, health care, administration, postal services, shops and restaurants, hydro power and windmill parks, military activities (Ahlenius *et al.*, 2005; Duhaime and Caron, 2006; Glomsrød and Aslaksen, 2009; Dittmer *et al.*, 2011; Conley *et al.*, 2013).

Additionally, the Arctic supports subsistence activities outside the cash economy such as fishing, hunting,

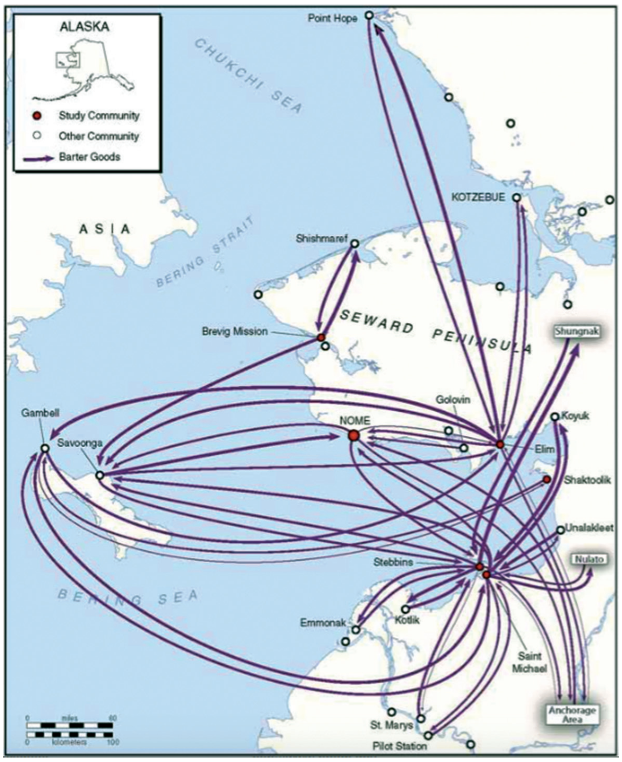

Fig.1 — Patterns of trade and barter between neighbouring human communities, regional hubs, and urban communities. Data collected between 2004-2006 in six western Alaska human communities. Source: Magdanz *et al.* (2007, p65).

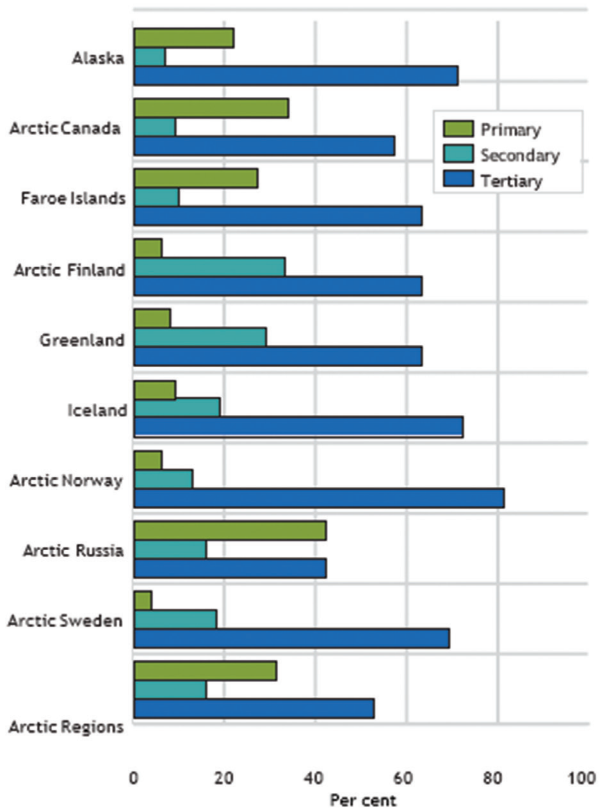

Fig.2 — GDP (%) by main industry in the different Arctic Regions (reference year: 2003) (Source: Duhaime and Caron, 2006, Figure 2.1 p.19). Primary sector: large-scale extraction of non-renewable resources, small-scale commercial fishing and forest exploitation; secondary sector: manufacturing and construction; tertiary sector: service industries.

caribou and reindeer herding, gathering, and traditional food processing (Ahlenius *et al.*, 2005, p.27; Glomsrød and Aslaksen, 2009). Subsistence activities are associated with significant traditional trading and bartering between different Arctic populations (Figure 1; Glomsrød and Aslaksen, 2009). Traditional activities are sometimes no longer enough to sustain families, with a push towards supplementing their income through the cash economy (Dana and Riseth, 2011).

The Arctic, at the macroeconomic level, displays intense economic activity linked to the exploitation of natural resources, and a very dominant service industry (Figure 2; Duhaime and Caron, 2006; Glomsrød and Aslaksen, 2009). Exploitation of natural resources includes geographically concentrated large-scale extraction of non-renewable resources such as hydrocarbons, nickel, diamonds and gold, as well as geographically widespread small-scale commercial fishing and forest exploitation. The public sector often accounts for 20-30% and the overall service industry for over 50% of all economic activity in the Arctic regions.

At the microeconomic level, the resource rent derived from production in the Norwegian oil and gas (offshore) sector has risen quite significantly in 2000-2004 compared to previous periods (Figure 3). Resource rents for renewable natural resources are much lower, with hydropower (green) and forestry (dark blue) associated with positive resource rents, commercial fisheries (orange) associated with negative but increasing rents, and aquaculture (turquoise) associated with positive and negative resources rents (Figure 4).

Local opportunities for development of economic activities arising with climate change in the arctic: potentially high economic benefits but for high economic costs in a high-risk environment. All industries operating in the Arctic region are faced with slightly different opportunities and constraints because of climate change, with potentially high economic benefits but for high economic costs. The receding ice sheet cover allows for increased duration and extent of physical access to natural resources such as fish and timber (renewable resources), oil, gas and minerals (non renewable resources). This increased access could translate into additional economic revenues for the fishing, timber, mining (oil & gas, minerals) industries. Numbers put forward more often than not fail to include costs and market price

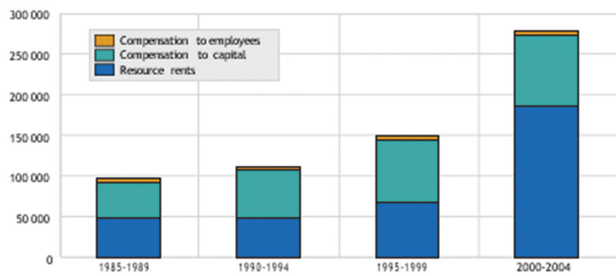

Fig.3 — Five-year average decomposition of gross production in the Norwegian oil and gas (offshore) sector (Source: Duhaime and Caron, 2006, Figure 1 p.24).

fluctuations which can influence profits greatly. The Arctic inherently remains a high-risk environment.

Most of the following descriptions and numbers rely on the use of models for predictions of future outcomes and are often subject to a high level of uncertainty. The quality of the outputs from such models depends on data quality, trends and understanding at the time the models were established. Estimations of potential gains are not always based on objectively measured data, with perceptions playing a big role. Predictions from such models should be considered with caution, especially when overly optimistic, as rewards may not fully materialise, or only in 2030-2050. It is not easy to determine whether actual gains will meet today's great expectations, nor how long it will be before they do.

The shipping (sea transport) industry would benefit from greater use of Arctic and circumpolar (sea transport) shipping routes such as the Northern Sea Route (the shipping lane along the Russian Arctic coast that connects Europe to the Asia-Pacific region), the Northwest passage (along the North American coastline), or the Bering Strait (53-mile strait between Siberia and Alaska) thanks to reduced ice cover extent and thickness and longer ice-free periods increasing seasonal access for maritime traffic (Peters *et al.*, 2011, Conley *et al.*, 2013, p.32-37). These routes cut down miles, shipping time and fuel costs, which combined with high fuel costs increase their appeal to the industry. Estimates of 40% shipping cost reduction and recent cost saving 'records' between Europe and Asia are widely quoted to illustrate the economic potential of these routes focusing on best possible outcomes only.

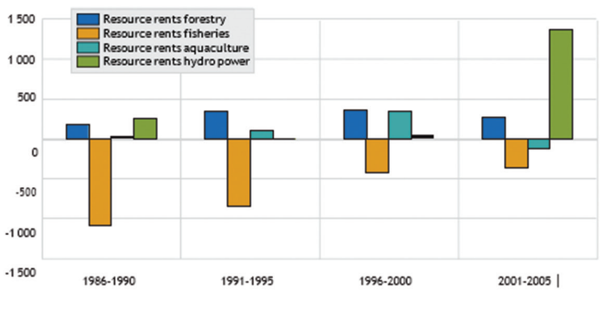

Fig.4 — Five-year average resource rents from the renewable natural resources in Norway (Source: Duhaime and Caron, 2006, Figure 2 p.25).

More recent studies accounting for ship performance in ice conditions are far less optimistic with only 5-16% cost saving now, and up to 29% in 2030 and 37% in 2050 (Liu and Kronbak, 2010; Peters *et al.*, 2011).

Actual cost savings need to offset higher costs of ice-graded vessels, non-regular and slower speeds, navigation difficulties and risks of accidents from poor visibility and ice conditions slowing ships down, as well as the need for ice breaker service (Liu and Kronbak, 2010). There are a limited number of public-use deep-water ports, re-fuelling stations, or reliable re-supply locations, limited communications and emergency response infrastructure including search and rescue capacity in the Russian Federation and Northern Europe and almost non-existent communications and emergency response infrastructure along the North American coastline (Valsson and Ulfarsson, 2011; Dawson *et al.*, 2014).

All these could reduce the appeal of using Arctic shipping routes compared to the Suez or Panama canals (Peters *et al.*, 2011). International shipping along the Northern Sea Route has decreased by half between 2011 (41 trips) and 2016 (19 trips) (Alexeeva and Lasserre, 2018). China however estimates that 1% of its freight could transit through the Northern Sea Route from 2020. Preparation includes a few publicised trials of transport along the Northern Sea Route and commissioning the construction of ice-grade vessels. Recent studies rather point to marginal and seasonal use of Arctic routes for international transport (Hugot and Umana Dajud, 2018; Theocharis *et al.*, 2018). At present, longer sea ice-free periods are not enough for transport companies, and these routes have so far remained excluded from their business strategies (Lasserre *et al.*, 2016).

The Arctic fishing and aquaculture industry would benefit from increased stock levels. Southern and pseudo-oceanic temperate fish species stocks are relocating North (Barents and Bering Seas), which could lead to unprecedented harvest levels most likely benefiting commercial fisheries (Hunt Jr. *et al.*, 2013; Christiansen *et al.*, 2014; Falk-Petersen *et al.*, 2015). The Barents Sea already displays higher levels of fish biomass density, with productivity at all trophic levels increasing with climate change and increased upwelling of nutrient-rich waters such as that of winter 2012. Actual streams of economic benefits depend on avoiding overfishing under yet insufficient Arctic fisheries biological data (Christiansen *et al.*, 2014).

Economic benefits are to be traded off with the negative impact of climate change and ocean acidification over calcareous shellfish (*e.g.* clams and oysters) and zooplankton (krill, pteropods consumed by salmons) (Ocean & Climate, 2015). It has been suggested that climate change could be directly or indirectly one of the causes of the disappearance of commercial species such as King Salmon off the coast of Alaska (Conley *et al.*, 2013).

Higher density of fish stocks would bring fishing effort down, but more difficult navigation in the Arctic generates extra costs (fuel, ice-grade vessels). Revenues from Arctic fishing would increase by 34% between 2000 and 2050 – less than 1% per year on average – with similar increase in costs (Lam *et al.*, 2016). Fishing is not profitable in itself but only through a multiplier effect, with an increase in household revenues by 32% over 50 years. At the local level, climate change can negatively impact subsistence fishing, for example in areas where it constitutes a major livelihood source (Himes-Cornell and Kasperski, 2015). In addition, overall costs also increase because of high monitoring and enforcement costs to mitigate illegal, unreported, and unregulated (IUU) fishing in the Arctic (WWF, 2008).

The oil and gas industry would benefit from increased physical access to oil and gas resources including offshore reserves in the Chukchi Sea. 400 oil and gas onshore fields north of the Arctic Circle account for approximately 240 billion barrels (BBOE) of oil and oil-equivalent natural gas – almost 10 percent of the world's known conventional resources (cumulative production and remaining proved reserves) (Bird *et al.*, 2008). The total undiscovered conventional oil and gas resources of the Arctic believed to be recoverable using existing technology are estimated to be approximately 90 billion barrels of oil, 1,669 trillion cubic feet of natural gas, and 44 billion barrels of natural gas liquids, with approximately 84% of the undiscovered oil and gas occurring offshore (Bird *et al.*, 2008). Oil and gas exploitation in the Arctic, however, comes with high costs for Arctic resistant infrastructure and operations, as well as capital costs for purchase of exploration licenses, leases, drilling permits, equipment and personnel (Conley *et al.*, 2013). Outdated infrastructure and lack of investment capacity are currently limiting the development of extraction activities in the Russian Arctic, despite gradual strategic convergence towards China since 2008 (Alexeeva and Lasserre, 2018).

Following a report by Lloyd's, a large UK-based insurance market, and Chatham House, a British think tank, in April 2012, not all insurers are happy to insure operations in the Arctic (*e.g.*, German bank West LB), partly `because of the logistical and operational challenges due to the harsh and unpredictable Arctic conditions (Conley *et al.*, 2013). The Dutch company Shell has pioneered efforts for offshore exploitation of oil and gas reserves in the Beaufort and Chukchi seas. The total investment cost for such operation is estimated to over US $4.5 billion for lease acquisition in 2005 and 2008, one sixth of its annual capital spending budget (Conley *et al.*, 2013). Total investment may exceed US $40-50 billion, which represents a significant financial risk for the company (Conley *et al.*, 2013). Shell suspended its Arctic operations in 2015.

The recent fluctuations in oil prices, combined with the exploitation of previously non-commercial natural reserves (*e.g.*, shale and other unconventional gas) have generally reduced incentives to operate in the Arctic (Conley *et al.*, 2013). There is still low competition from alternative energies – which have longer term potential – such as wind, waves, hydropower from the huge rivers that flow into the Arctic Ocean, and geothermal energy (Valsson and Ulfarsson, 2011).

The mineral extraction industry would benefit from increased physical access to mineral resources such as lead and zinc in Alaska, gold in Canada, rare earth elements in Greenland, diamonds and iron in Canada and Greenland, aluminium in Iceland, and nickel in the Russian Federation (Duhaime and Caron, 2006; Conley *et al.*, 2013). China is progressively building its strategy to defend its interests in the Arctic, positioning itself as a 'near Arctic state' (Lasserre *et al.*, 2015). In particular, Greenland could become a gateway for China's commercial entry into the Arctic region following recent discovery of large reserves of rare earth metals and increased Chinese strategic interest in these resources (Conley *et al.*, 2013; Gattolin, 2014). This is what seems to have motivated the United States of America to offer to buy Greenland, a topic prominent and hotly debated in the media in August 2019.

The GFMS index for base metals has increased by 300% between June 2002 and June 2007 (Conley *et al.*, 2013; Gattolin, 2014) whilst gold extraction has been put on hold in Alaska following low world market prices (Conley *et al.*, 2013). Mineral extraction in the Arctic comes at high infrastructure and operation costs to withstand the harsh weather conditions. Infrastructure development and maintenance (road or rail corridors) are often borne by government rather than industry. Infrastructure development could unlock exploitation of resources, *e.g.* copper exploitation in Alaska so far suspended for lack of infrastructure (Conley *et al.*, 2013; Melvin *et al.*, 2016).

Climate change in the Arctic seems to have extended access to areas of touristic value, benefiting the **Arctic tourism industry** directly. It has opened up previously inaccessible areas for exploration and use by expedition cruise ships as well as lengthened the shipping season (Dawson *et al.*, 2014). The Crystal Serenity, with her 1,200 passengers and a crew of 400, was the first cruise ship to go through the Northwest Passage in 2016, demonstrating that size is by no means restricted. There is globally increasing demand for 'remote' tourism experiences and for the unique and iconic landscapes and wildlife, driving an increase in Arctic tourism (Dawson *et al.*, 2014). Itineraries around Arctic Canada have more than doubled from 2005 to 2013, even if they remain limited to 30 itineraries a year (Dawson *et al.*, 2014).

Infrastructure and operation costs for Arctic tourism operators are decreasing with climate change (Dawson *et al.*, 2014). Transaction costs are however high for tourism in Arctic areas, with operation permits difficult to obtain in some countries or associated with a high opportunity cost for the country because of tax avoidance and lack of effective communication between government agencies (Dawson *et al.*, 2014). Information costs can be high for navigation in 'unchartered', 'wild' Arctic areas, because of incomplete or outdated maritime maps. Navigation accidents such as the grounding of the Clipper Adventurer in the summer of 2010 occurred because of nautical map inaccuracy (Supreme Court of Canada, 2018). Arctic tourism development can also generate resentment from local populations who may not wish their home to become a living museum (Antomarchi, 2017).

The small Arctic **manufacturing industry** would benefit from increased inputs availability such as fish for processing (Iceland, Greenland), rare earth minerals for electronics (Arctic Finland), and aluminium for smelting (Iceland) (Glomsrød and Aslaksen, 2009). As for other industries, high costs of capital, technology, qualified labour and transportation to consumption centres from manufacturing centres usually limit the development of the manufacturing industry in the Arctic (Conley *et al.*, 2013; Arctic.ru, March 2015). Changing and unpredictable climate conditions as well as thawing permafrost will likely weaken existing infrastructures and increase investment and repair costs.

The service industry serving local Arctic populations would indirectly benefit from increased economic activity in the region but also most likely incur additional costs for infrastructure development and maintenance not covered by the private sector – roads in particular (Conley *et al.*, 2013).

ENVIRONMENTAL CONCERNS

The main environmental concerns stem from the loss of pristine environment and unique Arctic ecosystems because of climate change, or from Arctic economic development pressures generating pollutions. One solution has been to create protected areas. For example, in the USA, the Alaska National Interest Lands Conservation Act established in 1980 the Arctic National Wildlife Refuge (ANWR), a 19 million acre protected wilderness area including caribou herds, polar bears, and mammals as well as numerous fish and bird species. The Russian Federation has also created several protected areas over its vast Arctic territory (Sevastyanov, 2018).

Arctic economic development is associated with a high risk of air and marine pollution, particularly from oil spills, Persistent Organic Pollutants (POP), heavy metals, radioactive substances, as well as the depletion of the ozone layer (Kao *et al.*, 2012; Conley *et al.*, 2013). Past experiences of soil rehabilitation after mining and clean ups of Cold War waste have led to high costs to human and environmental health: the 'develop now, fix later' strategy has incurred severe financial, social and political damage (Dance, 2015; Hird, 2016). Shell's operations in the Arctic had been slowed down before 2015 following damage to its oil spill barge, the Arctic Challenger, highlighting a lack of appropriate oil spill response measures in place (Conley *et al.*, 2013). Pollution generated by heavy diesel fuels of Arctic sea transport and tourism ships is a concern because of the accelerated sea ice decline it induces (Conley *et al.*, 2013). Concerns over pollution generated from mineral extraction have stalled gold mining in Alaska (Conley *et al.*, 2013). The high risk of oil spill and associated reputational damage this could cause, influential insurers such as Lloyd's getting 'cold feet' combined with the high financial costs and risks have led to Total and BP to back off from the Arctic earlier than Shell (Conley *et al.*, 2013).

Climate change externalities are a concern. Carbon emissions and pollutions cause more damage in the Arctic than elsewhere because of "polar amplification". Pollutions from Arctic shipping and tourism relying on heavy diesel fuels induce greater ice melting pack (Crate, 2012; Conley *et al.*, 2013; Whiteman *et al.*, 2013). Climate change induces thawing of permafrost, a normally permanently frozen soil found in high latitudes of the Arctic (Guiot, 2017). Whiteman *et al.* (2013) estimated that methane released only from Arctic offshore permafrost thawing would have a price tag of USD 60 trillion in the absence of mitigating action, representing about 15% of the average total predicted cost of climate-change impacts of USD 400 trillion. Mitigation could potentially halve the costs of methane releases (Whiteman *et al.*, 2013). Economic consequences are global, but about 80% impact the poorer economies of Africa, Asia and South America with increased frequency of extreme climate events (Whiteman *et al.*, 2013).

SOCIAL CONCERNS

The Arctic takes multiple forms, but with many internal tensions between industrial development and environmental protection, and with very different expectations over quality of life between traditional and westernised ways of life (Heininen and Exner-Pirot, 2018). Social and societal concerns arise with climate change itself or with economic development and industrialisation. Most of the social focus is on indigenous and resident populations of the Arctic who heavily depend on resources provided by their environment for their subsistence. With climate change, the receding ice sheet and unstable ice pack reduce game and sea mammal subsistence hunting and ice fishing opportunities (Ahlenius *et al.*, 2005 p.4; Himes-Cornell and Kasperski, 2015). Economic development generates increased competition within and between industries for access to resources across a three dimensional space. There is increased competition for fishing resources between coastal trawl and subsistence fishers in southern-based fisheries (Ahlenius *et al.*, 2005 p24). There is competition between subsistence fishing and offshore oil and gas extraction (Alaska) and between subsistence herders and oil and gas extraction (Russian Federation) (Duhaime and Caron, 2006; Conley *et al.*, 2013)

As illustrated by historical changes in Russian governance, heavy dependence of Arctic communities on the public sector makes Arctic population vulnerable to industry and government withdrawals, with dire social consequences for employment alternatives are extremely scarce at best (Glomsrød and Aslaksen, 2009; Amundsen, 2012). Small businesses and enterprises face adverse conditions to their own development, with wage inflation, high living costs and competition from public sector employment (Heininen and Exner-Pirot, 2018).

Increased Arctic tourism is supported by indigenous and resident populations so long as it is managed well and respects sensitive and culturally important shore locations, wildlife and other natural landscapes (Dawson *et al.*, 2014). This has occurred de facto in Arctic Canada following 'good will' and high ethical standards of expedition cruise operators, but may be prone to change with new comers entering the industry as there is no formal regulation safeguarding against 'bad' practices. The same applies to scientific research: concerns over impacts of scientific research vessels on subsistence activities have led to the development of a Community and Environmental Compliance Standard Operating Procedure (Konar *et al.*, 2017).

The Arctic displays worse-than-average health levels, the result of colonisation and marginalisation: lower life expectancy, higher frequency of psychological problems, drug additions, depression, domestic abuse and suicide (Heininen and Exner-Pirot, 2018; Zhuravel, 2018). Concerns from indigenous population health have in some places stalled mineral extraction (*e.g.*, uranium in Alaska, Conley *et al.*, 2013). Elsewhere, it is because of strong indigenous concerns and social contestation that mineral extraction was stopped (*e.g.*, gold and coal in Alaska, Conley *et al.*, 2013). Arctic populations are very sensitive to the boom-and-bust nature of mineral extraction: they depend on transfers from southern regions of their country even though they are yearning for more financial independence (Heininen and Exner-Pirot, 2018). It seems wealth created in the Arctic now would tend to stay there, thanks to diversification of activities, particularly services, reducing the economic dependence of the Arctic on other regions (Larsen, 2016).

Social problems are still very real in the Arctic, fueled by poverty, food insecurity, young people moving away from traditional lifestyles, marginalisation of women and traditional Arctic economies, and lack of access to information and knowledge for Arctic communities (Crate, 2012; Dalseg and Abele, 2015; Hodgkins and Weber, 2016; Mathisen *et al.*, 2017; Dalseg *et al.*, 2018; Malik and Melkaya, 2018). Forced displacement and family separation practised in Arctic Canada in the 1950s and 1960s have also left very deep and lasting social scars (Healey, 2016).

THE SEEDS ARE SOWN, BUT THE 'COLD RUSH' IS STILL DORMANT

The Arctic somehow seems to have come of age. All Arctic States seem to position themselves in the starting blocks by strategically securing access rights to Arctic resources and circumpolar routes, but without violating any international binding agreement. Industries in the Arctic could potentially reap very high economic rewards, but the overall high investment and operation costs keep it a financially high-risk environment to operate in, and reduce its competitiveness compared to other regions of the world. The 'cold rush' has not really started yet, as all stakeholders seem to be exercising relative caution in relation to the huge financial, reputational, diplomatic and political risks involved with economic development of the Arctic.

Political challenge ahead: reconciling different perspectives, including environmental and social concerns, to make the most of new opportunities in the arctic.

Very contrasted perspectives and social values coexist, with an Arctic between global common good and sovereign state property. The Arctic means: '**wilderness**' to environmental organisations for preservation or bequeath to future generations, a '**frontier**', source of energy and minerals, to industry, a '**home**' to over a million indigenous people, and a place of '**strategic and geopolitical interest**' to government for military, energy and environmental security (adapted from an original citation by Sheila Watt-Cloutier in Ahlenius *et al.*, 2005). The main political challenge ahead would seem to lie in the conciliation of such contrasted perspectives and ensuring they can live alongside one another peacefully, minimising conflicts whilst keeping up with the very fast pace of economic development associated with a 'cold rush'.

One possible way to achieve this would be through integration of science, economics and diplomacy for conflict resolution (Berkman and Young, 2009). Science can provide a 'neutral', mutually accepted and recognised basis for establishing trust, monitoring, reporting and objective verification by and between all parties. Economics can provide assessment tools that consider trade-offs and resource use conflicts.

Integration of science, economics, law and diplomacy could help bring together not only globally well-connected climate change winners in the Arctic but also losers from the local to the global level. Such integration and establishment of discussions at multiple levels, in turn, could lead to realise economic opportunities arising with climate change in the Arctic while taking environmental and social concerns into account. The exact pathway will most likely vary within countries, between countries and between the local and the global levels, with the choice and choice processes to determine such pathway the responsibility of local, national and international decision-makers.

Within countries, economic and human development can be identified along three models: the 'North American model' which is a neo-liberal regime at the last frontiers (highly concentrated around extraction of non renewable resources), the 'Scandinavian model' which follows the redistribution model of Northern Europe, and the 'Russian model' which is heavily shaped by its political and military history (Glomsrød and Aslaksen, 2009). New institutional approaches for improved natural resource management have been explored in some Arctic areas with promotion of co-management and joint stewardship. This restructuring of power and responsibilities among stakeholders requires strong political will to shift to decentralised and collaborative decision-making associated with improved coordination between indigenous populations and government (Glomsrød and Aslaksen, 2009).

Policies for promotion of external interests in the Arctic that recognise local populations combined to improved data over economic activities and distribution of benefits, social and environmental indicators have the potential to help minimise conflicts between stakeholders (Ahlenius *et al.*, 2005). Some Arctic countries have adopted measures to prevent pollution associated with legally recognised compensation mechanisms, and established national strategies for adaptation to climate change and energy security (Ahlenius *et al.*, 2005; Amundsen *et al.*, 2007). For instance, Canada has extended the reach of its Arctic Waters Pollution Prevention Act (Berkman and Young, 2009). Some Arctic countries have set up national research programmes with an objective to inform action in the Arctic for adaptation under climate change (The Arctic – The Canary in the Mine. Global implications of Arctic climate change. Norwegian-French conference in Paris, 17 March 2015). Such national initiatives, however, do not allow to resolve transboundary issues that rather call for supra-national approaches (Berkman and Young, 2009). Arctic research and exchanges going beyond national boundaries, for example facilitated by the Arctic University, could foster innovation focused on issues specific to polar environments (Hall *et al.*, 2017).

Between Arctic countries, there are a number of jurisdictional conflicts (Figure 5), increasingly severe clashes over the extraction of natural resources and transboundary security risks partly inherited from the Cold War era. A new 'great game' is emerging among the global powers with global security implications (Berkman and Young, 2009). Regional and international cooperation seems to be generally favoured in spite of States taking a stand over their sovereign rights, including through unilateral sovereignty extensions in disputed or international areas. The Russian Federation planted a flag under the North Pole while filing in an official extension request to the Commission on the Limits of the Continental Shelf of The United Nations Convention on the Law of the Sea, UNCLOS, of 10 December 1982. The status of the Northern Sea Route and Northwest Passage is disputed, some seeing them as international maritime routes under common international jurisdiction, whereas Canada is claiming sovereignty over the Northwest Passage and the Russian Federation over the Northern Sea Route (Lasserre, 2017).

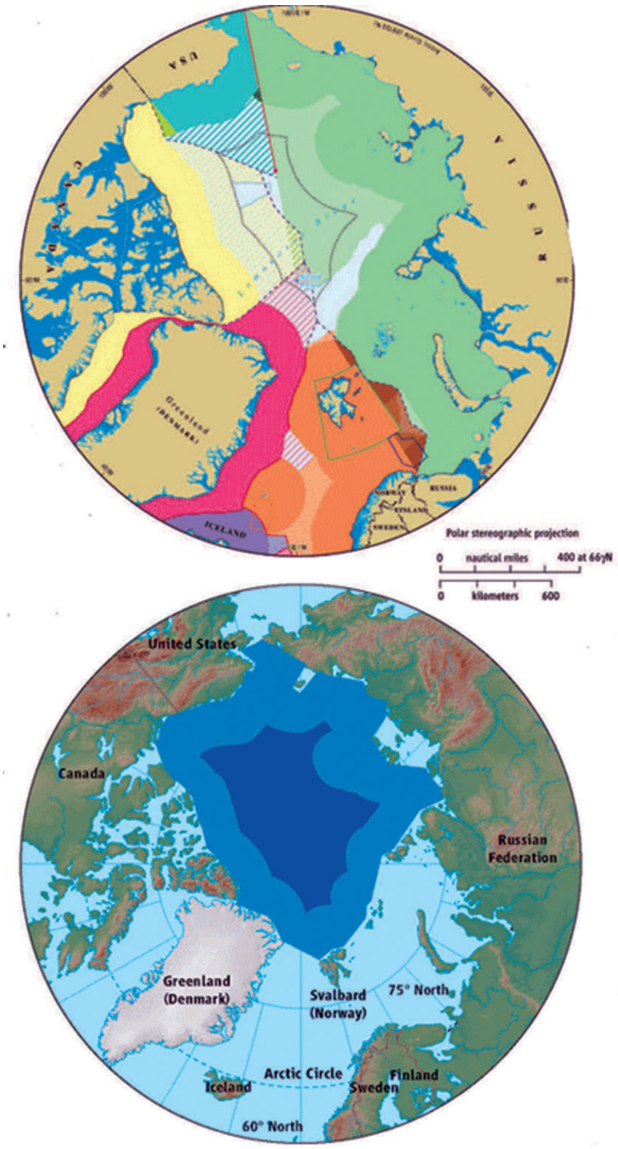

Fig.5 — Arctic sea ice Jurisdictional representations of the Arctic Ocean with boundaries based on (top) sea floor as a source of conflict among nations (different colours) and (bottom) overlying water column as a source of cooperation, with the high seas (dark blue) as an international space in the central Arctic Ocean surrounded by economic exclusive zones (EEZ, light blue). Source: Berkman and Young (2009).

The United Nations Convention on the Law of the Sea, UNCLOS, of 10 December 1982 (Montego Bay Convention) is considered one of the main binding agreements providing a legal framework for activities in the Arctic to this day. UNCLOS helps regulate access to Arctic resources, maritime traffic and pollution through clear identification of national jurisdictions and provision of a mechanism for dispute resolution (Berkman and Young, 2009). UNCLOS grants states bordering the Arctic Ocean sovereign rights for areas under their jurisdiction. In the Ilulissat Declaration of May 2008, countries part of the Arctic Council have reaffirmed their commitment to the legal framework provided by UNCLOS, and to the harmonious settlement of any competing claims that may arise.

In addition to UNCLOS, a number of other international conventions are relevant to the Arctic: the International Convention for Safety of Life at Sea (SOLAS) which focuses on safety requirements, the International Convention for the Prevention of Pollution from Ships (MARPOL 73-78) which focuses on environmental protection, the Convention on Standards of Training of Seafarers (STCW) which focuses on training and competency for personal safety at sea, and the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) which provides a guide for international cooperation and protection of the marine environment and applies to part of the Arctic.

More recently, a number of framework agreements have been established, in particular in relation to shipping in the Arctic, search and rescue operations and pollution management. They provide additional guidance and structure for international cooperation in the Arctic. The International Maritime Organization (IMO) has facilitated the adoption of a series of measures such as the International Code for Ships Operating in Polar Waters, better known as 'Polar Code' or 'Code for polar navigation'. The Polar Code includes amendments to the SOLAS Convention (adopted in 2014 and binding since 1st January 2017), to the MARPOL 73-78 Convention (adopted in 2015 and binding since 1st January 2017) and to the STCW Convention (adopted in 2016, binding since 1st July 2018).

An international agreement signed at Ilulissat on 3rd October 2018 aims to prevent unregulated commercial fishing on the high seas in the central Arctic Ocean. This agreement is signed by Canada, China, Denmark for Greenland and the Faroe Islands, Iceland, Japan, the Republic of Korea, Norway, the Russian Federation, the United States of America, and the European Union. Signatories commit to conducting commercial fishing only within the framework of regional fisheries organisations acting in accordance with recognised international standards. This agreement applies for 16 years and will be automatically extended every five years after that.

All these agreements have been possible thanks to exchanges at the international level in intergovernmental discussion platforms, leading to implementation of coordinated actions with benefits for all ("win-win"). Such platforms include intergovernmental organisations such as the United Nations and its agencies (including IMO), and international fora such as the Arctic Council.

The Arctic Council is formed by 8 states with land within the Arctic Circle: the United States of America (Alaska), Canada, Denmark (Greenland and the Faroe Islands), Iceland, Norway, Sweden, Finland, and the Russian Federation. The Council is a high level intergovernmental forum for Arctic governments and peoples (http://www.arctic-council.org). It is the main institution of the Arctic and was formally established by the Ottawa Declaration of 1996 to provide a means for promoting cooperation, coordination and interaction among the Arctic States, with the involvement of the Arctic Indigenous communities and other Arctic inhabitants on common Arctic issues, in particular issues of sustainable development and environmental protection in the Arctic. The Council is a "weak institution", with no regulatory authority (Chater, 2018), but has successfully facilitated the negotiation of binding agreements between the 8 Arctic countries. Examples include the Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic (2011), the Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic (2013) and the Agreement on Enhancing International Arctic Scientific Cooperation (adopted in Fairbanks, Alaska in May 2017, binding since May 2018).

The Arctic Council has been instrumental in the production of scientific assessments such as the Arctic Climate Impact Assessment (ACIA) by its Arctic Monitoring and Assessment Programme (AMAP) working group, Conservation of Arctic Flora and Fauna (CAFF) working group, along with the International Arctic Science Committee (IASC). The Arctic Council has also been the force behind the establishment of a report on human development in the Arctic (Larsen and Fondhal, 2014), and on Arctic environment resilience and ways to ensure its integrity (Arctic Council, 2016).

The Council has successfully brought Arctic issues to the attention of global fora. For example, the 2001 Stockholm Convention on Persistent Organic Pollutants was in part informed by the work of the Arctic Council. Adopted in Stockholm in May 2001 and implemented from May 2004, the Convention aims to reduce levels of persistent organic pollutants accumulating in the environment. It recognises that "Arctic ecosystems and indigenous communities are particularly at risk because of the biomagnification of persistent organic pollutants and that contamination of their traditional foods is a public health issue" (preamble of the Convention).

A number of international scientific monitoring and research bodies are setting up and participating to scientific initiatives and projects in the Arctic. Such international collaborative scientific projects could provide a basis to build trust and enhance Arctic state cooperation through establishing scientifically sound common baselines (Berkman and Young, 2009). These include (but are not limited to) the International Arctic Science Committee (iasc.info), and the European Polar Board (www.europeanpolarboard.org). Several non-Arctic states have become involved in Arctic scientific activities. China considers itself a "near-Arctic state" and is involved in scientific research there (Alexeeva and Lasserre, 2018). Japan has also developed its research activities in the Arctic following revival of interest for the place (Coates and Holroyd, 2015). There are a few training centres and universities in the Arctic itself or dedicated to Arctic issues, among which the University of the Arctic, a network of universities, colleges, research institutes and other organisations concerned with education and research in and about the North (www.uarctic.org). Several academic journals dedicated to polar environments, draw and share evidence from the natural sciences, social sciences and humanities alike (*e.g.*, The Northern Review, Arctic and North, The Polar Journal, Polar Record, and Advances in Polar Science). There is therefore ample grounds for scientific exchange and collaboration on the Arctic.

The Arctic captivates minds and enthrals imaginations as much as ever. There is real potential to harness and develop existing institutions (*i.e.* organisations, binding and non binding agreements) and build up existing institutional capacity based on current and emerging needs. New institutional needs have already emerged in the Arctic with current economic development. So far, the precautionary principle and constructive approaches for action have been aplied. The pace of economic development will be much faster when the cold rush is triggered. One of the challenges will be to build up existing capacity and develop safeguards fast enough to keep up with the fast pace of economic development and changes induced. There is certainly strong potential for creating shared economic wealth and well-being, with benefits for all. Actual choices made by Arctic countries and industries for economic development, coordination and cooperation within the coming years will significantly shape the Arctic of tomorrow.

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Small islands, ocean and climate

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The physical characteristics of small islands (limited land area, small plains, high exposure to unpredictable climate variations and sea-related hazards) and their human characteristics (strong dependence on subsistence activities and ecosystems) explain their potentially high vulnerability to environmental changes (*i.e.*, changes in the ocean and sea-related hazards). They have become symbolic of the threats associated with climate change: rising sea levels, increase in cyclone intensity and frequency, as well as ocean warming and acidification. Although a wide diversity of answers is to be expected from one island system to another, small islands are exposed to significant threats: reduction in their surface area, increase in coastal erosion, degradation of coral reefs and mangroves, etc. The impacts on land (soil, water, fauna and flora) and marine resources (reefs and fisheries) are major, jeopardizing the future of human survival on many islands. Consequently, island societies have to face an extremely pressing challenge.

Regardless of their political status[1], small islands, whether isolated or part of an archipelago, have to face a number of constraints inherent to their small size (ranging from less than 1 km² to several thousand km²) and to their geographical remoteness from major world centers of activity (for example, economies of scale are scarce, affecting their competitiveness, education system, etc.). In particular, their physical (limited land area, small plains, high exposure to climate variations and sea-related hazards) and human characteristics (strong dependence on subsistence activities and ecosystems) explain their high sensitivity to environmental changes and natural disasters. Such features directly generate a series of impacts that, on the continent, would generally be easily attenuated in space and time (Duvat & Magnan, 2012). Small islands are therefore territorial systems that are both vulnerable and reactive, placing them at the forefront of the consequences of environmental changes related to the excess of anthropogenic greenhouse gases in the atmosphere, particularly those affecting the global ocean (surface water warming and acidification). The political representatives of these insular states often present their islands as the first victims of climate change. However, the threats to small islands are not so marginal, since in some ways they are the same as those faced by the vast majority of the world's coastlines. Therefore, beyond their specific characteristics, there are lessons to learn from these "miniature lands".

This article follows the simple logic of the causal chain of impacts starting from physical, climatic and oceanic processes, and leading to the consequences on the ecosystems and resources of island systems. The issue of environmental changes and their relationship with the unsustainable development[2] process will then be addressed, followed by a few key takeaways to conclude.

1 Independent State like the Maldives or Mauritius; State in free association with its former colonial power, such as the Marshall Islands (USA), or the Cook Islands (New Zealand); overseas territory that is part of a larger territory, such as the Overseas Territories of France, for example.

2 Term that describes the unsustainable nature of current development patterns.

THE PHYSICAL PROCESSES AT WORK

The island nations have been sounding the alarm since the late 1980s: environmental changes related to climate change, such as the gradual degradation of vital resources like fresh water, or the occurrence of devastating extreme events, *e.g.*, cyclones, raise the question of their chances of survival over a timespan of a few decades. Small islands have thus become emblematic examples of the threats associated with climate change, and even metaphors of the environmental challenge faced by modern humanity, "alone on its tiny planet" (Diamond, 2006). This diagnosis is based on scientific grounds, which are directly related to anthropogenic greenhouse gas emissions into the atmosphere for nearly 150 years, and can be classified into four categories: rising sea levels, extreme events, global ocean warming and acidification.

Rising sea levels

Rising sea levels as a consequence of climate change is undoubtedly the most publicized phenomenon, especially for small islands. Catastrophic interpretations relay poorly the more cautious scientific conclusions, with some sections of the media announcing the impending disappearance of low-lying islands (especially the Maldives, Kiribati and Tuvalu), while others proclaim the imminent flooding of coastal plains where populations and economic activities are concentrated.

Although such claims can be questionable, as the responses of island systems to climate pressure will necessarily be diverse, it remains an undeniable fact that sea levels have been rising for more than a century due to anthropogenic climate change. Why? Sea level rise results from the increase in the temperature of the lower atmospheric layers, which both warms surface ocean waters, causing their expansion, and melts continental ice (mountain glaciers, Arctic and Antarctic ice caps). Combined, these two processes increase the volume of ocean water, which, schematically, tends to "overflow". The average rate of sea level rise was 17 cm across the globe throughout the 20th century, corresponding to about 1.7 mm/year (Church *et al.*, 2013).

Recent scientific research highlights two elements. Firstly, the fact that the ocean does not rise at the same rate everywhere: the eastern Indian Ocean and the Central Pacific, in particular, experience high rates of sea level rise, with values reaching, for example +5 mm/year in Funafuti (Tuvalu) (Becker *et al.*, 2012). Secondly, the scientific community points out that sea level rise, which has accelerated since the early 1990s[3], will continue to do so over the next century. The worst case scenario[4] predicts an average sea level rise of 45 to 82 cm by 2100 (Church *et al.*, 2013). Furthermore, this trend is partly irreversible, because of the latency characterizing the oceanic and atmospheric processes. It will cause sea levels to carry on rising for at least several centuries, even if all greenhouse gases emissions were to stop tomorrow (Solomon *et al.*, 2009, Levermann *et al.*, 2013).

The consequences of this accelerated sea level rise will be all the more serious for small islands, as they have a high coastal index (coastline to land area ratio) and their populations and activities are mostly concentrated in the coastal zone. Obviously, the situation of low-lying islands (atolls) is of particular concern, as the example of the Kiribati Archipelago (Central Pacific) will illustrate below.

In 1989, the United Nations adopted a specific resolution on the adverse effects of rising sea levels on islands and coastal areas, officially recognizing the high vulnerability of these territories to climate change. A few years later, the United Nations Conference on Environment and Development (Earth Summit, Rio, 1992) emphasized once again the particular case of small islands. More recently, during the Third International Conference of the United Nations on Small Island Developing States, held in early September 2014 in Samoa, one of the key themes addressed was climate change and, in particular, rising sea levels.

3 The global average was +3.2 mm/year between 1993 and 2010 (Church et al., 2013).

4 Models supporting the latest IPCC report considered four main scenarios regarding greenhouse gas concentrations in the atmosphere by the end of the century. These scenarios are Representative Concentration Pathways (RCPs), ranging from the most optimistic (RCP2.6) to the most pessimistic (RCP8.5).

Extreme events: cyclones, distant swells and El Niño

Our understanding of the interactions between the ocean and the atmosphere is still incomplete and limits our ability to model some climate phenomena, and therefore to predict future development of extreme events (storms and El Niño). However, the pressure of these extreme events on small islands is expected to increase.

The energy generated by tropical cyclones is far greater than that of temperate depressions, with wind speeds that can exceed 350 km/h.

These winds can destroy vegetation, infrastructure and buildings. Cyclones are often accompanied by heavy rainfall too (up to 1,500 mm in 24 hours), leading to overflowing riverbeds, and even catastrophic flooding. In addition to these weather effects, cyclonic swell impacts coastal areas, causing even more destruction, as cyclones are associated with storm surge[5]. The consequences of marine inundation (waves and storm surge) are obviously amplified when it is combined with flooding from inland waterways. Cyclonic swell, which often reaches a height of 4-6 m at the coast, can also cause marked erosion peaks (coastline retreat by 10 to 15 m, foreshore lowering) or, on the contrary, strong accretion along the coast due to the accumulation of sand and coral blocks torn from the reef (Etienne, 2012).

Given the complexity of such processes, it is difficult at this stage to predict how cyclones and their impacts on small islands will evolve as a result of climate change. However, on the basis of the latest IPCC report, the main facts to bear in mind are that: *(i)* the frequency of cyclones will not necessarily increase in the future; *(ii)* the most intense cyclones are expected to increase in intensity; and *(iii)* their trajectories, *i.e.* impact areas, are very likely to change in the future. On this basis, and despite uncertainties about cyclone development, an increase in their destructive impacts is expected on small islands: firstly, because sea level rise will allow cyclonic swell to spread farther inland; and secondly, because the intensification of the most powerful cyclones will worsen their destructive effects on coastal areas. For example, erosion is expected to accelerate in places where cyclones are already causing erosion peaks.

Likewise, storm development in northern and southern temperate zones and at high latitudes, which remains difficult to predict, will have consequences for the evolution of sea-related hazards in insular environments.

In fact, it is now well established that the powerful swell produced by these storms travels great distances across the ocean and causes significant damage to islands thousands of kilometers from where it formed (Nurse *et al.*, 2014). For example, in December 2008, distant swells caused significant damage in many western Pacific states, such as the Republic of the Marshall Islands, the Federated States of Micronesia, and Papua New Guinea (Hoeke *et al.*, 2013).

Finally, it is still extremely difficult to predict the evolution of El Niño, even though at least four of its manifestations severely disrupt insular environments. Firstly, the significant changes in surface ocean temperatures occurring during El Niño events are reflected in some regions by marked temperature peaks, responsible for devastating coral bleaching episodes[6] (95 to 100% coral mortality in the Maldives and the Seychelles in 1997-1998). Secondly, El Niño events result in an increased number of cyclones in areas usually less exposed, as is the case for the Tuamotu Archipelago in French Polynesia: while cyclone frequency is normally one every 20 to 25 years, five cyclones passed over the northwestern islands of this archipelago within the space of six months during the 1982-1983 El Niño episode (Dupont, 1987). Thirdly, El Niño causes major disruptions in rainfall patterns: heavy rains in some areas (Central and Eastern Pacific) and severe droughts in others (Western Pacific, with strong impacts in Kiribati and

5 Abnormal sea level rise due to low atmospheric pressure (-1 mb = +1 cm) and wind surge (water accumulation on the coastline) is adding to wave action (flow and ebb on the shore).

6 When the coral thermal tolerance threshold is exceeded (around 30°C), coral expels zooxanthellae (symbiotic photosynthetic algae that partly feed coral), thus whitening and risking massive mortality. Prolonged bleaching can cause the death of a whole reef.

the Marshall Islands, for example). Some islands, such as those south of Kiribati, can thus experience droughts lasting one or two years.

Ocean warming

The rise in ocean surface temperatures is another problem, combining with the previous phenomena. A large part of the energy accumulated by the climate system is stored in the ocean, with the consequence that the first 75 m of the water column warmed by 0.11°C per decade between 1971 and 2010 (Rhein *et al.*, 2013). Substantial warming is now also clearly measurable down to a depth of at least 750 m (Arndt *et al.*, 2010). The consequences of such changes will be major in offshore areas (migration of species, including those that are fished, disruption of oxygen exchanges, etc.), as well as in coastal areas, with severe impacts on coral reefs, which are very sensitive to temperature rise. The gradual upward trend in ocean surface temperatures, combined with the onset of destructive thermal peaks occurring during El Niño episodes, gives rise to concern that bleaching events may become more frequent and even persist (Hoegh-Guldberg, 2011; Gattuso *et al.*, 2014). This could cause many species to disappear.

Ocean acidification

In tandem with climate change, pollution from greenhouse gases is beginning to produce a higher content of dissolved CO_2 in the ocean, a process better known as ocean acidification (Gattuso & Hansson, 2011). Ocean acidification is also referred to as "the other CO_2 problem" (Turley, 2005; Doney *et al.*, 2009). In fact, the oceans have absorbed about a third of anthropogenic CO_2 emissions since the Industrial Revolution. However, the increased CO_2 concentration in seawater reduces its pH, making it more acidic. Predictions for the 21st century indicate a decrease in the global mean pH, which may reach 7.8 by 2100 (Ciais *et al.*, 2013), compared with 8.18 before the industrial era and 8.10 at present.

This phenomenon has already had, and will continue to have, a significant impact on the ocean's basic chemistry and, through a domino effect, on marine organisms (reduced calcification rates of many organisms with calcareous skeletons or shells) and ecosystems (Pörtner *et al.*, 2014; Gattuso *et al.*, 2014; Howes *et al.*, in press). Hence, experts estimate that the impacts of acidification on coral reefs will become very significant above an atmospheric CO_2 concentration of 500 ppm (Hoegh-Guldberg *et al.*, 2014)[7].

The future vulnerability of small islands to climate and ocean changes will therefore largely depend on the way these four pressure factors (sea level, extreme events, ocean warming and ocean acidification) evolve. These island systems are reactive because they are highly dependent on environmental conditions. Hence, acidification combined with surface water warming will have even more negative impacts if coastal ecosystems (reefs, mangroves, etc.) are already subject to strong anthropogenic pressure, especially if they have already undergone significant functional degradation. This also holds for threats posed by rising sea levels and the occurrence of more intense tropical cyclones: the more natural coastal systems have been disrupted – sometimes irreversibly – the more their innate ability to adapt will be lessened in the future, and the greater the impacts of extreme events and more gradual changes will be. Thus, the unsustainability of our current development patterns (degradation of marine and coastal ecosystems, dissociation of modern society from environmental constraints, development of areas exposed to hazards, etc.) is at the heart of the threats that climate change poses for coastal areas, and especially islands (Duvat & Magnan, 2014).

IMPACTS AND VULNERABILITY OF SMALL ISLANDS

To understand why small islands are at the forefront of impending environmental changes, it is necessary to go into detail concerning the combined impacts of rising sea levels, extreme events, ocean warming and ocean acidification.

7 The atmospheric CO_2 concentration threshold of 400 ppm was exceeded in May 2013 at the monitoring station in the Mauna Loa observatory (Hawaii). As a comparison, this same station reported 386 ppm in 2009.

What impacts are expected?

Climate models do not yet provide accurate evolution scenarios at the scale of different oceanic sub-regions. However, the current predictions, together with the available knowledge on the responses of island systems to different types of natural and human pressures, enable scientists to determine the main effects of climate change on these environments. The consequences for the evolution of small islands and their main coastal ecosystems, coral reefs and mangroves, will be discussed in turn below.

Reduced island surface area and coastline retreat

It is impossible to predict the response of island systems to the pressure resulting from climate change because of the multitude of factors involved and the complexity of their interaction. These factors can be both natural (sediment reservoirs, storm impacts, response of coral reefs to the pressure associated with climate change, etc.) and anthropogenic (interference of coastal development with natural coastal processes, impacts of human activities and public policies on ecosystems, etc.). Hence, a decrease in island surface area is expected over the next few decades, particularly for coral islands. A country like the Maldives, where 80% of the land is less than 1 m above sea level, is very likely to undergo a significant reduction in its surface area due to sea level rise. However, this stress factor – like others (storm frequency and intensity, deterioration of coral reef health, etc.) – will have varying impacts from one island to another, depending on the geomorphological and human context.

For instance, islands already affected by erosion or with heavily developed coastlines will not benefit from any natural elevation mechanism to adjust to sea level rise. Such an adjustment mechanism will be possible only if there is an underwater sediment reservoir capable of supplying the shore, but also an area free of any development along the coast where sediment can accumulate. However, these two conditions are currently met only on a limited number of inhabited islands; on the other hand, such a natural adjustment mechanism is likely to succeed on some islands with little or no development.

Similarly, on the coastal fringe of higher islands, lowlands will gradually be reclaimed by the sea, where no accretion mechanism will cause them to rise or extend offshore, unless technical interventions, such as backfilling, prevent this and keep these areas above sea level.

In some cases, a decrease in the surface area of low-lying islands will probably jeopardize their viability, as their resources will become insufficient to meet their inhabitants' needs. The coastal plains of higher islands will also be subject to climate pressures, resulting in impacts on communities that will be all the greater when population pressure is high and food production systems are developed (Nurse *et al.*, 2014).

Consequently, the evolution of coral islands and coastal plains will vary from one place to another, depending on a large number of factors whose development cannot necessarily be predicted.

Coral reefs under threat

Coral reef behavior will play a key role in the response of many islands to the impacts of climate change.

However, the future of reefs depends on a combination of factors, the main ones being the rate of sea level rise, ocean surface temperature, ocean acidification rate, current coral vitality and ability to withstand ecological disruptions, and the extent to which their resilience is weakened by human activities (Gattuso *et al.*, 2014). The rates of sea level rise predicted for the coming decades theoretically allow coral to compensate with growth for rising sea levels, as they can grow 10 to 25 mm/year. During the last increase in sea level, the vast majority of reefs followed the rise step by step (keep-up reefs) or after a time lag (catch-up reefs). However, these various elements remain theoretical because, in reality, coral behavior depends on the ecological conditions prevailing in the different parts of the ocean. In areas where reef health is good, coral eventually grows with rising sea levels, but in places where reef health is significantly deteriorating, coral is likely to disappear. Various factors, ranging from local to global, determine the quality of ecological conditions. At the global level, they will deteriorate due to ocean acidification, which, as mentioned earlier, reduces the calcification rate of calcareous skeleton organisms and, at the same time, their resistance to natural and anthropogenic stressors.

At both local and regional levels, the main factors influencing coral behavior are ocean surface temperatures (mean value and intra- and interannual variations), pH, storms and the extent to which humans disturb the environment. As for coral bleaching, the models developed for Tahiti (French Polynesia) over the period 1860-2100 show that surface temperature remained below the critical threshold[8] until 1970, meaning that no bleaching episode had occurred previously (Hoegh-Guldberg, 1999). Since that date (and since which time there has been evidence of an increase in ocean temperatures due to climate change), ocean temperatures have consistently exceeded this threshold during El Niño events, leading to inevitable bleaching events.

Based on the predicted changes in ocean temperatures, the models forecast annual bleaching from 2050 onwards, thus undermining coral's ability to survive. The increasing frequency of these events might not give coral reefs enough time to regenerate between two heat peaks. However, this remains a hypothesis because the responses of coral reefs vary from one region to another, depending on ocean circulation and depth: shallow reefs are generally more affected by thermal peaks and less resilient than those developing in a more oceanic environment (close by deep waters and intense exchanges with the ocean water mass). Also, at a local level, the responses of various coral species differ. A single species does not inevitably react identically to two thermal stresses of the same intensity, as observed during a monitoring program carried out in 1996, 1998 and 2002 on coral reefs of the Persian Gulf (Riegl, 2007). In 1996, branching coral of the genus Acropora was completely decimated, but regenerated rapidly and was not affected in 2002. This suggests that coral does have a certain capacity to adapt. Observations made in the Eastern Pacific lead to the same conclusion. The 1982-1983 El Niño episode was more destructive than that of 1997-1998, prompting the hypothesis that disasters contribute to selecting the most resistant individuals (Glynn *et al*., 2001). Coral resilience also depends on its impairment due to diseases, whose development has been promoted by thermal peaks in some regions (the Caribbean, for example). Finally, coral resistance and resilience depend largely on the extent of human disturbance. It is now estimated that 30% of the world's coral reefs are already severely damaged, and close to 60% may be lost by 2030 (Hughes *et al*., 2003).

Anthropogenic pressure on reefs is likely to increase in island systems due to generally high population growth.

Why is so much importance given to coral reef development when assessing the fate of small islands? The partial or total disappearance of coral reefs would result in not only the prevention of any mechanism for vertical adjustment of these islands and coastlines to changing sea levels, but also an increase in coastal erosion. Firstly, reef death would reduce the supply of freshly crushed coral debris; secondly, it would increase marine energy at the coast, causing wave-induced erosion, especially in storm conditions. In this configuration, the factor playing a crucial role in preserving coral coasts will be the state of inert sediment stocks[9] that can be used in marine processes, thus compensating for the reduced supply of fresh coral debris. The role of the sands accumulated on shallow seabeds should not be overlooked, as some islands with a poorly developed reef (narrow or present on only part of the coastline) have formed and continue to grow in response to the shoreward migration of these ancient sands (Cazes-Duvat *et al*., 2002).

Where ecological conditions are favorable for coral development, reef flats with no coral cover, such as those of Kiribati and Tuamotu, for instance, consisting of a conglomerate platform, could be colonized by new coral colonies. This same applies to coasts bordered by a rocky reef with no coral cover. In this case, reef development could contribute to reef flat elevation, thus allowing them to follow a rise in sea level. Such a development would clearly be beneficial to the vertical growth of low-lying islands and their associated coastal plains, as well as their replenishment with coral debris. As a result, not all coastlines will erode. It should ne-

8 Although the maximum temperature tolerated by coral varies from one region to another – this threshold being higher in seas than in oceans – bleaching is generally likely to occur when seawater temperature exceeds 30°C.

9 Sediments produced by previous generations of coral reefs.

vertheless be noted that coral development would not produce immediate benefits for human communities.

Coral colonization and growth processes are very slow and very likely to slow down in the future, as ecological conditions are deteriorating.

Islands and coasts that do not elevate will be more regularly submerged during spring tides, storms and El Niño episodes, while those that do have an upward growth will not necessarily be more vulnerable to flooding than they are at present.

What is the future for mangroves?

Mangroves play just as important a role as coral reefs in preserving low-lying islands and sandy coasts, and in protecting people from storms. These coastal forests generally expand in areas where they have not been cleared and where the mudflats they colonize continue to be supplied with sediments. In many atolls, inside the lagoon, mangrove extension can be observed as a result of the colonization of sandy-muddy banks by young mangrove trees (Rankey, 2011).

How will climate change impact mangroves? Theoretically, a rise in sea level is likely to cause inshore migration, as the different ecological areas making up the mudflat also tend to adapt by migrating in this direction. However, beyond the sea level rise, two factors will play a key role: the sedimentation rate and level of human pressure on the ecosystem. In favorable conditions (active sedimentation and reduced human pressure), rising sea levels can be offset by raising shallow seabeds. In this case, mangroves remain or continue to expand offshore. The most sensitive areas are undoubtedly those that are already affected by humans and/or severe erosion, causing mangrove destruction.

It is worth noting that the responses of island systems to climate change and ocean acidification are not unequivocal, as they depend on a combination of factors, whose interactions can show spatial variations, even over short distances. In addition, current knowledge about coral and mangrove resilience faced with natural pressures is still insufficient to make a definitive assessment. While it is undeniable that reefs will be under increased pressure in the future, the results of recent research put into perspective the even more pessimistic findings of early studies. Furthermore, as reef behavior will play a crucial role in the evolution of coral islands and coastal plain sandy coasts, where morpho-sedimentary processes are complex and spatially variable, it cannot be concluded that all coral islands, for instance, will be rapidly swept off the face of the planet. In addition to the uncertainties prevailing regarding a number of processes, there is also considerable doubt as to the timetable within which some island systems will find themselves in a critical situation.

What will be the impact on island resource systems?

To consider the next link in the chain of impacts of climate change and ocean acidification on human communities, the focus will now turn to the impact of physical disturbances on land (soil, water, fauna and flora) and marine resources (reefs and fisheries) of low-lying islands and coastal plains of high mountainous islands.

On land

Land resources are going to decline as a result of various processes (Nurse *et al.*, 2014; Wong *et al.*, 2014). First of all, the rise in atmospheric temperature leads to increased evapotranspiration[10], which dries out the soil and causes an increase in the consumption of brackish shallow groundwater by plants. This groundwater uptake should not be overlooked, as measurements on Tarawa Atoll (Kiribati) have shown that the most common tree, the coconut tree, released at least 150 liters of water per day into the atmosphere through transpiration.

Under these conditions, the expected increase in groundwater pumping by coconut trees and other types of vegetation will significantly increase the pressure already exerted on these reserves by humans to meet their needs. The deterioration of soil quality and dwindling water resources will further reduce the agricultural potential. This will result in a decline in production, especially for island agriculture, representing a

10 Evapotranspiration refers to the different phenomena related to plant evaporation and transpiration. These two processes are linked because, through transpiration, plants release water absorbed from the ground into the atmosphere, thereby contributing to the water cycle.

serious challenge regarding food security. An increase in external dependency will ensue, in particular for rural atolls in many coral archipelagos. Soils will also deteriorate under the effect of salinization due to rising sea levels, and more frequent coastal flooding will occur on the islands and coastal plains that cannot be elevated. However, few edible plant species tolerate salt, except coconut trees, which can only do so up to a certain threshold, beyond which they die. Moreover, the reduction in farmed land, especially coconut groves, will mean that fewer building materials are available. In addition, the gradual shift in island farming practices towards species that are less resistant to climatic and marine pressures than native species – for instance, banana trees are less resistant than pandanus and coconut trees – may increase the scale and frequency of food shortages (this is what happened, for example, in the Maldives following the damage caused by the tsunami in 2004) and trade deficits (as in the case of the West Indies following the passage of Hurricane Dean in 2007) in the future.

Climate change will cause quantitative and qualitative changes in water resources, depending on several factors. The most important is sea level, whose elevation will inevitably reduce the volume of underground freshwater lenses.

According to the Ghyben-Herzberg principle, which governs the functioning of aquifers, any rise in sea level causes a reduction in their volume. More frequent or even systematic coastal flooding during high spring tides is the source of repeated saltwater incursions into the groundwater, thus contributing to the deterioration of its quality. Islands and coasts subject to severe coastal erosion will be more affected than others by the decrease in volume and quality of the underground lenses. Another important factor is rainfall, which determines the replenishment rate and frequency of underground freshwater lenses and rivers running through the coastal plains. Currently, there is no reliable means of predicting rainfall trends. Moreover, there are still uncertainties regarding the underground freshwater resources of some high mountainous islands. It is thus impossible to identify which islands and archipelagos will be most affected by the deterioration of water resources. A reduction in the volume of water available is to be expected in areas where droughts will be more frequent and/or last longer. Consequently, the water will become more saline, increasing the frequency and severity of crop mortality peaks (for coconut trees and taro[11], in particular), as is already being observed. Water removal from freshwater lenses during a drought further reduces their thickness. This means that in times of water shortage, this groundwater, which is crucial for the survival of many islanders, may become unfit for consumption. If the drought persists, the islands' rainwater tanks rapidly become empty and this issue could then jeopardize the habitability of some low-lying islands. Individual access to water will also decrease as a result of the high population growth in these areas.

At sea

As highlighted in the latest IPCC report (Pörtner *et al.*, 2014; Hoegh-Guldberg *et al.*, 2014), there is currently very little information concerning the impacts of climate change on fishery resource distribution. The intense pressures already affecting coral reefs in some of the most populated areas will increase wherever population growth remains high.

As various factors contribute to reef deterioration in these areas, available per capita reef resources will decrease. Moreover, these resources play an important role in the daily diet of island communities, including those on islands where the need for imported products is high (Nurse *et al.*, 2014). This is even more of an issue when considering that possible changes in ocean currents could reduce the abundance of pelagic species in some ocean regions, thereby preventing a consumption transfer to these species. The fishing industry as a whole is therefore being questioned, from natural resources to fishing facilities (ships, ports, etc.), the latter also being destabilized by rising sea levels, extreme events and other stress factors (economic crisis, for example). On top of this, of course, overfishing severely depletes fish stocks in coastal waters and lagoons, as well as offshore.

Even though island systems will have a differentiated response to climate change and ocean acidification,

11 A root vegetable, emblematic of the Pacific civilizations (for consumption and ceremonies). Each family owned a share of the "taro garden".

and despite the remaining uncertainties, it is clear that the already major environmental constraints will keep increasing. As a consequence, the already limited island resources will decrease or become more uncertain than they are at the moment. Therefore, the viability of some coral islands and island states could eventually be called into question. However, at present, the main threat to these islands' sustainability is unsustainable development, which, over the past few decades, has depleted the available resources and in some ways reduced their resilience to natural pressures (Duvat & Magnan, 2012, 2014). In other words, the main problems facing coral islands and coastal plains today are pollution, land disputes, depletion of natural resources, etc., in addition to the impacts of climate change and ocean acidification.

This conclusion is not a denial that climate change and acidification have, and will have, major impacts; rather it is a justification that existing insular communities will have to meet a challenge that is unprecedented compared with what they are already facing today. With relatively little room for maneuver, they will have to deal with the impacts of climate change, exacerbated by the major environmental disturbances of recent decades, which have greatly increased ecosystem vulnerability. Under these conditions, climate change and ocean acidification will act as accelerators of current trends. By reducing the surface area of islands in a context of high population growth, climate change will, in some cases, lead to land conflicts, for example. Furthermore, by reducing reef resources while food needs continue to increase, climate change and ocean acidification will most likely accelerate reef deterioration and death in some regions. The pressure on water resources will also increase. Overall, it is likely that the population will become more concentrated in capital cities, currently the only areas benefiting from alternative solutions (desalinated water, imported food). This will inevitably have consequences, mainly for food security and human health.

Due to the combination of unsustainable development, climate change and ocean acidification, scientists now fear that some archipelagos will no longer be habitable within a few decades.

BETWEEN ENVIRONMENTAL CHANGES RELATED TO ATMOSPHERIC CO_2 AND UNSUSTAINABLE DEVELOPMENT: THE SYMPTOMATIC CASE OF ATOLLS

This third section highlights the importance of placing the pressures related to climate change and ocean acidification in a broader context of anthropogenic pressures.

The aim is to show the extent to which future threats first take root in current problems of unsustainable development, as illustrated, in particular, by the severe degradation of coastal ecosystems and uncontrolled urbanization. In this case, climate change and ocean acidification act as pressure accelerators on the living conditions of insular communities.

The case of the coral archipelago of Kiribati (Central Pacific) illustrates this point (Duvat *et al.*, 2013; Magnan *et al.*, 2013). The focus here will be only on the impacts of climate change, since the consequences of ocean acidification are for the moment too complex to determine in this specific case. A brief reminder of the country's natural constraints and socio-economic changes over the past two centuries will help to explain the pressures currently affecting the country, and how these will be amplified by climate change. When considering the future of these island areas and populations, this demonstrates the major importance of combining the physical (climatic and chemical processes, ecosystems, etc.) and human dimensions (cultural relationship to resources and risk, development patterns, etc.) in order to understand these systems in all their geographical and historical complexity. In other words, their vulnerability to future environmental changes does not solely depend on the evolution of the climate/ocean relationship. This basic reasoning is fundamental to understanding vulnerability in all its dimensions, but also to devising adaptation strategies that are locally relevant, consistent and realistic in their implementation.

Like Tuvalu and the Maldives, Kiribati mainly consists of atolls that evolve based on coral response to variations in weather and sea conditions. Its exclusive economic zone (EEZ) is vast (3.5 million km²) and contrasts with the modesty of its land area (726 km²), comprising a large number of scattered islands.

On an atoll, the dominant feature is the lagoon, which is bounded by a ring of coral that forms islets usually less than 1 km² in area. Not all of the land on the islands is habitable on their entire surface due to the presence of swamps and mangrove mudflats, the high instability of their shorelines and their low elevation. With highest points of between 3 and 4 m, they are at risk of sea flooding. As they are young (between 2,000 and 4,000 years old), composed of sand and coral rubble and exposed to marine processes, their soils are poor and their plant resources little diversified. Water is scarce, brackish (2-3 g salt/l) and very sensitive to climate variations. It is supplied by rainfall, which infiltrates the ground to form shallow freshwater lenses (about 1 to 2 m deep) proportional in size to the islands. In the southern Kiribati islands, water supply is unpredictable owing to the periods of drought linked to El Niño events, which can last up to two years.

At a human level, three thousand years of history have shaped a territorial organization originally based on a two-pronged strategy: ensuring each family has access to the entire diversity of land and sea resources, and managing these resources rationally. The fact that the islands are divided into strips of land linking the lagoon to the ocean enabled each family to exploit the different natural environments. Dwellings were generally built some 20 to 60 meters from the lagoon shore, sheltered from the sea swell. Inland, the islanders cultivated coconut and pandanus trees (for wood, palms and fruits), and, in very low-lying areas, taro. The families also shared the management of the fishing grounds along the sea coast and the fish ponds in sheltered areas, and collected shellfish on the muddy foreshore of the lagoon. The island communities stockpiled food and coconuts in anticipation of harsh weather conditions (Di Piazza, 2001). This system ensured that the population's diet was optimally diversified and helped to cushion crisis periods caused by fluctuations in the different resources. Today, this way of life has almost disappeared, especially on the most urbanized and most populated islands (*e.g.*, the South Tarawa Urban District).
In less than two centuries, Kiribati has experienced five profound changes:

1. Dwellings have been grouped into villages on the rural atolls and into urban areas on the Tarawa atoll.
2. Power has been concentrated in the capital atoll, Tarawa, and the system of self-management by each atoll has been abandoned.
3. Complex customary law has given way to simplified written law.
4. The subsistence economy has been replaced by a market economy.
5. The traditional land tenure system has been dismantled.

Recent decades have been marked by a population explosion in the capital atoll, driven chiefly by improvements in the health sector. Kiribati's strong population growth – from 38,000 inhabitants in 1963 to over 103,000 in 2010 (+171%) – is mainly concentrated in the urban district of South Tarawa, which is now home to half the country's population on only 2% of the territory, with an average density of 3,125 inhabitants per km². This situation has brought on *(i)* a rapid degradation of ecosystems and resources, *(ii)* the loss of traditional ties linking cultural identity with the environment, and *(iii)* the inhabitants' high level of exposure to weather and sea-related hazards as they have settled in flood-prone and unstable areas, and *(iv)* a growing dependence on international aid and food imports.

Finally, all of these changes, placed in the context of the conclusions of the first and second sections (coral reef weakening, coastal erosion, marine submersion, depletion of water resources, etc.), go a long way towards explaining Kiribati's vulnerability to climate change and ocean acidification.

KEY TAKEAWAYS AND AVENUES TO EXPLORE

Their intrinsic characteristics, both physical and anthropogenic, place small islands at the forefront of threats associated with climate change and ocean acidification. However, their situation raises more universal questions in that, ultimately, most coastlines across the world are also threatened by extreme weather, marine events and the progressive deterioration in the living conditions of ecosystems and human communities. Hence, contrary to what might be believed, small islands do not present such marginal situations. Consequently, they have important lessons to teach, including the three main issues highlighted in this article.

Firstly, the vulnerability of coastal areas to future environmental changes does not depend solely on rising sea levels and the evolution of extreme events. Although this review demonstrates that these two pressure factors are very important, they are often the only ones mentioned in vulnerability assessments carried out in coastal areas. An analysis based on these factors alone is therefore biased as it does not take into account the consequences of either global warming or ocean acidification. These two processes are capable of weakening the core of the resource systems of island territories, in particular the fundamental links of the food chain at the coast (*e.g.*, coral reefs) and offshore (*e.g.*, phytoplankton).

Secondly, this vulnerability does not depend solely on natural pressures either, such as occasional hazards and more gradual changes in environmental conditions. Human factors will also play a decisive role in the future of islands and, in a larger sense, of their coasts (Duvat & Magnan, 2014). If climate change and ocean acidification are real threats – and it would be irresponsible and dangerous to deny it – then tomorrow's problems are closely tied to current patterns of land and resource use that are not sustainable.

This means that engaging, as of now, in proactive policies designed to readjust spatial planning, protect the environment and change the relationship between human communities, their economies and the marine and coastal resources, would be a major step towards adaptation to climate change and ocean acidification.

The identification of anthropogenic pressure factors presently at work ultimately provides many pointers for devising and starting to implement adjustments to environmental changes (Magnan, 2013). Human responsibilities are powerful levers that must be used to limit future threats.

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Ocean, climate change and migration

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Changes in the ocean and the cryosphere play a key role in the Earth's climate. Both the regulation role and services provided by these ecosystems are under threat. The impacts of these changes on ecosystems and human societies are now obvious. They jeopardize the safety of the most exposed populations, especially in coastal areas, on small islands, on mountains and in polar regions, and have economic, social and cultural impacts on all human communities, including those living away from these areas. For the most vulnerable populations, environmental migration can be an answer. Anticipating and adapting to these changes would help to reduce impacts on natural environments and on the communities that depend on them.

OCEAN, CRYOSPHERE AND CLIMATE

The ocean has absorbed 93% of the excess heat as well as nearly a quarter of the CO_2 emissions generated by human activities, thus regulating the climate system and limiting the extent of atmospheric warming. However, the ocean is severely disrupted by these major changes and is gradually getting warmer, more acidic and less oxygenated. These modifications also contribute to sea level rise and increase the frequency of destructive weather events, such as cyclones, spring tides, and ocean heat waves.

The cryosphere is also changing due to an overall reduction in ice cover: ice sheet retreat, sea ice melt and permafrost (permanently frozen land) thawing.

CHALLENGES

All the inhabitants of the planet depend on the ocean and the cryosphere. These natural environments, which are involved in the climate regulation and the water cycle, also support many human activities: food (fisheries and aquaculture), employment, tourism, health, leisure, etc. Fish products account for 20% of the protein intake in the human diet (excluding cereals) and provide a livelihood for tens of millions of people (in 2016, 60 million people worked in the primary sectors of capture fisheries and aquaculture, according to the FAO). Eighty percent of international freight transport is seaborne.

In 2010, 28% of the world's population (1.9 billion people) lived within 100 km of the coast and less than 100 m above sea level, and 11% (680 million people) lived less than 10 m above sea level (a number expected to grow to 1 billion by 2050). Approximately 10% of the world's population (4 million) live in the Arctic or in high mountain regions (670 million people). More than half of the world's population now lives in megacities, many of which are located near the coast.

Low-lying islands and coastal zones (including deltas, wetlands, etc.), from polar to tropical regions, are at the forefront of climate change due to their exposure to extreme events, the vulnerability of the ecosystems on which they depend for their natural resources, and the increase in pressure from human activities. Lower coastal areas, such as great delta plains, are particularly attractive and the most densely populated areas in the world because of the resources they provide and their access to the sea.

Climate change-related modifications that affect the global ocean and the cryosphere have direct consequences on island and coastal populations, but their repercussions go beyond these regions: the environment, the economy and the social life of many communities can be jeopardized.

Sea level rise, extreme events and the water cycle
Rapid sea level rise and more frequent extreme events are threatening millions of human lives as well as their livelihoods, and they will require multi-billion dollar investments in coastal infrastructure.

Sea level rise accelerated between the mid-20th century and the past few decades.

The ocean is warming up and expanding, thereby increasing its volume. The water inflow resulting from continental ice melt is adding to the problem. From 1994 to 2018, the ocean level increased by 8.5 cm, *i.e.* an average rate of more than 3.5 mm/year. However, this rate varies widely from a region to another. In Southeast Asia, for example, the ocean is rising very rapidly, up to 15 mm/year in some areas. Conversely, it is falling on the Alaskan coasts. This can be explained by the fact that the ocean's heat is unevenly redistributed by ocean circulation. Average sea level rise strongly depends on atmospheric greenhouse gas emission rates. In 2100, this average is estimated to vary between +0.43 m and +0.84 m, depending on the IPCC scenario considered.

This increase in average sea level is causing coastal erosion, a phenomenon that will have significant impacts on all lowlands: in the Arctic (where it is combined with the permafrost thawing and the decline in seasonal sea ice extent), in densely populated coastal cities that concentrate many economic activities, in delta areas and on islands.

Coral atolls are not static lands. They will undergo both erosion and sediment accretion caused by stronger waves. For example, out of 33 coral islands studied in the Solomon Islands, 5 have disappeared and 6 are experiencing severe erosion. In Tuvalu, with an increase in average sea level of about 15 cm between 1971 and 2014, the small islands have decreased in size, while the larger populated islands have maintained or increased their land area, except for Nanumea Island. Out of the 709 islands studied, approximately 73.1% have a stable surface area, 15.5% have an area that has increased and 11.4% have an area that has decreased over the past 40 to 70 years. Nevertheless, the ability of coral islands to maintain their surface area by naturally adjusting to sea level rise could be reduced in the coming decades as a result of the combined effects of higher sea level rise, increased wave strength, and the impacts of ocean warming and acidification on reefs.

In the Arctic, the combined effects of changes in the ocean and the cryosphere will be intertwined. The decrease in seasonal ice cover reduces soil protection and the increase in ground temperature weakens the stability of frozen soils. Currently, 178 Alaskan communities are facing severe coastal erosion and 26 are in a critical situation.

Climate change will also be associated with a higher frequency of high-intensity cyclonic storms. Floods and stronger waves will exacerbate coastal erosion. IPCC projections show that for many coastal areas, extreme events related to rising waters levels (floods) that currently occur every 100 years could occur once a year by the end of the century.

The impacts can affect ecosystems as well as the services they provide to the economy but also the coastal infrastructure, the habitability of the region, the livelihoods of the communities and their cultural and aesthetic values. Coastal facilities (housing, infrastructure, industry, agricultural and aquaculture activities) are particularly vulnerable to these weather events, which can result in the loss of human lives as well as significant economic damage.

In 2015, Cyclone Pam devastated Vanuatu, causing US$449.4 million in damage to a country with a GDP of US$758 million. In 2017, Cyclone Winston killed 43 people in Fiji and resulted in losses equivalent to one-third of the country's GDP. In 2017, Hurricanes Maria and Irma passed over 15 Caribbean islands and nations, and the cost of total repairs is estimated at US$5 billion. In 2018, Cyclone Gita affected 80% of Tonga's population.

Inland saltwater intrusions as a result of sea level rise and flooding will alter water groundwater (drinking water sources) and irrigation water, reducing arable land and water reserves. Thus, there is therefore growing concern that some Island States may become uninhabitable, with consequences in terms of population resettlement and state sovereignty. Many cases of saltwater intrusion affecting freshwater resources and crops have also been reported in delta areas. It is estimated that approximately 260,000 km² of land was temporarily submerged in the 1990s/2000s. Brackish water intrusions have been observed in the Delaware estuary in the USA, in the Ebro Delta in Spain and in the Mekong Delta in Vietnam. Agriculture, especially rice-growing, can be affected. In Bangladesh, the cultivation of oilseed, sugarcane and jute has ceased. Freshwater fish will lose some of their habitat, thus affecting fishing communities. Other consequences are the salinization of drinking water resources and the spread of cholera virus, as for example in the Ganges Delta.

In addition, changes in the water cycle – *e.g.*, the intensity and frequency of rainfall associated with seawater evaporation – increase the risk of flooding in some regions and drought in others. They affect water resources and promote epidemics. There are therefore increased threats to public health, food security and economic activities (fishing and tourism). Changes in the cryosphere will also have consequences for the safety of mountain communities that depend on glacial meltwater for their supply. Adapting to these phenomena will require the implementation of water regime regulation systems (*e.g.* rainwater and water from glacial melting ice management).

Affected marine biodiversity: what are the impacts on livelihood?

Physical and chemical changes affecting the ocean and the cryosphere will have significant impacts on marine and coastal organisms and ecosystems, which, in turn, will affect the livelihoods of millions of people who depend directly on these ecosystems and the many services they provide.

Ocean warming, acidification and deoxygenation affect benthic and pelagic marine species, large predators, and degrade ecosystems such as reefs, mangroves, coastal marshes, seagrass beds, and kelp forests.

The abundance and distribution area of many species are changing with environmental disruptions. Marine resource availability and abundance are therefore modified. Northward migration of some species, biological events (*e.g.*, breeding) that occur earlier in the season, and a global change in species distribution, are already being observed.

Coastal ecosystems protect coasts from erosion (coral reefs absorb 97% of wave energy) and provide populations with a variety of resources (food, mangrove wood, substances used in traditional medicine, etc.). These ecosystem services will be affected by climate change. The fishing and aquaculture sectors are impacted by marine wildlife migration and the changes in the marine environment. Ocean acidification, for instance, affects phytoplankton, fish larval growth, some mollusks' shell-building process or even the development of coral reefs, which support thousands of marine species.

Migration of vulnerable populations

These environmental phenomena and changes have a direct impact on various aspects of human safety and on the environmental, economic, political and social factors of human migration.

Small Island Developing States (SIDS), whose economies are closely linked to fisheries and tourism, are among the most vulnerable.

The impacts of climate change will exacerbate inequalities, cause population migration, and intensify competition for access to resources, which in turn will increase the risk of conflict, especially for the most vulnerable populations.

Coastal transformation has cultural impacts, particularly on low-lying islands. Studies led in Tuvalu show that, over the past 40 years, climate change has affected population mobility and places of residence and has grouped communities together in the least risky areas. Population relocation affects societal structures, lifestyles and livelihoods, and is accompanied by a loss of cultural heritage and identity.

It is estimated that the sea level rise caused by 2°C global warming by the end of the century would lead to flooding of lands where 280 million people live. While the risks are higher for low-income coastal areas and low-lying islands, this issue also concerns developed countries. In the USA, hurricanes have caused human migration and have had significant economic impacts. These movements of populations linked to extreme events interact with other migration pressures due to environmental and/or economic and political causes.

The combination of adaptation solutions will vary depending on the anticipated and observed impacts, the geographic location of populations, the adaptability of societies, and the establishment of new governance modes. The relocation of communities and economic activities is increasingly seen as an adaptation solution to climate change. However, it is accompanied by discussions on the costs and impacts on the well-being of relocated people. Population migration from coastal areas and lowlands is already underway in many regions: Alaska, Guatemala, Colombia, the Caribbean Islands and Vietnam. In Papua New Guinea, half of the inhabitants of the Carteret Islands are expected to be displaced on Bougainville Island by 2020. Relocations are also in progress on the Solomon Islands, in Alaska, and on the west coast of the USA.

As early as 2014, Fiji also successfully implemented programs to relocate people from some villages (such as Vunidogoloa in Vanua Levu, for example) in the wake of erosion problems. The relocation of populations will become an increasingly significant societal challenge for island and coastal communities.

In parallel, other migration strategies can be implemented. Thus, in many parts of the world, rural populations affected by recurrent hazards migrate on a temporary or seasonal basis. This allows them to make up for temporary income losses and provide for their families through urban or abroad employment.

Some Pacific countries, for example, participate in seasonal labor movement programs set up by New Zealand, Australia or Canada. Although these programs have not been developed directly in response to global warming issues, they could nevertheless benefit populations affected by the impacts of climate change who are seeking to diversify their sources of income through seasonal employment abroad. Other bilateral or regional agreements of this kind could be envisaged in the future to support the populations most affected by the impacts of climate change, particularly in Island States.

Ocean, climate change and human migration: Importance of the IPCC Special Report "Global Warming of 1.5°C"climatique de 1,5 °C »

In October 2018, the IPCC published a Special Report entitled "Global warming of 1.5°C". Echoing the requests already made in 2009 during COP15 in Copenhagen by a group of countries that are among the most vulnerable to climate change, this report owes its existence mainly to the representatives of Small Island Developing States (SIDS), members of the Alliance of Small Island States (AOSIS). In 2015, by the end of COP21, this group of countries had succeeded in having their vulnerability in the face of growing climate threats recognized through the inclusion, in the texts of the Paris Agreement, of three statements that are essential to their future: both SIDS and Least Developed Countries (LDCs) are vulnerable countries; this fact requires financial assistance from developed countries, specifically for adaptation measures; the insecurity they face could decrease if global warming were ? limited to +1.5°C. To endorse this last statement, the SIDS asked the IPCC to issue a Special Report to scientifically prove the relevance of this temperature requirement. It should be recalled that global warming impacts directly and dangerously the ocean ecosystem surrounding small islands, exacerbating sea level rise, cyclones, storms, and ocean acidification and deoxygenation.

Emphasizing the urgency of a real awareness of the future of the planet in the event of 1.5°C global warming, the IPCC experts have analyzed with unprecedented accuracy the damage we would suffer by 2100 if we do not act to limit the rise in global temperature to 1.5°C compared with the years 1850-1900 (this reference period corresponding to industrial development in western countries, and therefore the beginning of greenhouse gas emissions). This figure, however, should not be seen as the solution to live in a better world, but rather as a remedy for the worst, which will not cure global harm.

Indeed, even if States agreed at the international level to making the necessary mitigation and adaptation efforts needed to achieve this target of 1.5°C, the fact remains that the many regions mentioned in the analysis of the challenges posed by ocean and cryosphere changes would continue to experience increased climate risks. And this even if they are already facing them and become more and more vulnerable.

Let us remember some of the major aspects of this 1.5°C Special Report with regard to migration. At present, and in view of published data, the IPCC is not in a position to accurately assess the level of correlation between increases of 1.5°C, 2°C, or 3°C on the one had, and increasing human mobility on the other hand. This difficulty also stems from the fact that migration depends on many and often interconnected economic, political and social factors that remain extremely complex and specific to each country or population. However, it is clear that migration is closely linked to multidimensional insecurity and poverty, which are strongly correlated with climate change.

It should be noted that, according to this Special Report, an increase in emigration could be statistically correlated with rising temperatures in communities directly dependent on agriculture. In addition, according to a study by the Organization for Economic Co-operation and Development (OECD), an average temperature rise of 1°C would be associated with a 1.9% increase in bilateral migration. In the event of 2°C global warming by the end of the century, significant population movements could occur in tropical regions, over distances exceeding 1,000 km. Among the countries likely to be forced into further climate migration are the SIDS, which actively promoted this report and are at the forefront of climatic threats because of their direct exposure to an increasingly changing and dangerous ocean environment.

This Special Report points out, above all, that compliance with the 1.5°C limit is crucial to a fundamental principle now enshrined in the Paris Agreement, namely the fairness between individuals, nations and generations. It should be recalled that climate change and its harmful consequences impact nations and peoples in very unequal ways. Industrialized countries are the least vulnerable and best equipped to face and adapt to climate change. Conversely, non-industrialized countries, which emit low levels of greenhouse gases, have a much more limited capacity to adapt. However, these economically vulnerable countries are the ones most severely and frequently affected by the most damaging climate disruptions. Inequality of responsibilities, wealth, impacts, and means of protection constitute the ethical backdrop against which IPCC experts call on rich countries to focus their discussions and actions beyond their geographical and political borders and economic concerns – and, indeed, beyond Nationally Determined Contributions (NDCs) alone.

The IPCC therefore claims two global imperatives that resonate with the principle of fairness between individuals, nations and generations: sustainable and global development is now urgently needed to fight not only climate change, but also poverty.

The international laws for Ocean and Climate

Bleuenn Guilloux

The interactions between Ocean and Climate Systems are difficult to envisage together legally, because existing frameworks are fragmented and complex to grasp. On the one hand, the international ocean law can be characterized as a comprehensive framework, erecting a global architecture. It consists of a broad range of sectoral and regional arrangements, within the unified legal framework of the 1982 UN Convention on the Law of the Sea (hereinafter UNCLOS)[1]. The "constitution for the oceans" (T.B. Koh, 1982) is the result of the codification process of the Law of the sea and the formation of new legal rules (*e.g.*, the Exclusive Economic Zone (EEZ) or the status of archipelagic States). It defines the rights and obligations of States conducting maritime activities (navigation, exploitation of biological and mineral resources, marine scientific research, etc.), according to a zonal division of seas and oceans into zones under national sovereignty or jurisdiction (internal waters, territorial sea and contiguous zone, EEZ, continental shelf) and, zones beyond the limits of national jurisdiction (High seas, the Area)[2]. Since it came into force on the 16th November 1994, more than ten years after its signature in Montego Bay (Jamaica), the International Community has shown a growing concern for many issues related to the uses of seas and oceans and the protection of the marine environment. The topics of major concern are the collapse of most fisheries stocks, the destruction of marine and coastal habitats and biodiversity loss, the sustainable use and conservation of biodiversity of areas beyond national jurisdiction, land-based and marine pollution, and, in recent years, climate change impacts.

Rather than a comprehensive regulatory framework, the climate international law can be described, on the other hand, as a "regime complex", *i.e.* a network of partially overlapping and non-hierarchical regimes governing a common subject-matter[3].The UN climate regime is the cornerstone of the international Law on climate change. It has developed through arduous and protracted international negotiations, aiming at consensus among States and group of States with diverging interests, goals and expectations. The 1992 UN framework convention on Climate Change (hereinafter UNFCCC), which came into force the same year as the UNCLOS in 1994, provides the framework for stabilizing GHG atmospheric concentrations "at a level which would prevent dangerous anthropogenic interference with the climate system" (Art. 2)[4]. The UNFCCC has been complemented by the 1997 Kyoto Protocol to the UNFCCC (hereinafter

1 The UNCLOS was signed on December 10, 1982 (1833 UNTS 3) and entered into force on November 16, 1994. It has 168 State parties in July 2019.

2 For a general schematic of these zones, see https://www.geoportail.gouv.fr/donnees/delimitations-maritimes (last consulted July 2019) and of France, https://limitesmaritimes.gouv.fr/ressources/references-legales-en-vigueur-limites-despace-maritime (last consulted July 2019).

3 R. O. Keohane, D. G. Victor, "The Regime Complex of Climate Change", Perspectives on Politics, Vol. 9, No.1 (March 2011).

4 The UNFCCC was adopted in New York on May 9, 1992 (1171 UNTS 107). It was opened for signature at the Rio De Janeiro Earth

KP), setting quantified emission limitation and reduction commitments for developed Parties[5]. The 2015 Paris Agreement (hereinafter PA) specifies the UNFCCC ultimate objective, by setting the result-based temperature objective for all Parties "of holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (Article 2(1)(a))[6]. Besides the UN treaty-based regimes, the climate regime is prone to virtually encompass all sectors of activity or environmental problems through Conferences of parties (hereinafter COP) and Meetings of Parties to the KP (hereinafter MOP), to integrate new regimes or, to coordinate or cooperate with other regimes and fields of international law such as trade law, human rights and the law of the sea.

As framework conventions, the UNCLOS and the UNFCCC are the starting point of new specific legal regimes which evolve over time. With their respective "ethos", context of negotiation, legal scope and character, objectives and mandate, membership, norms, underlying principles and experts, they are loosely coupled. They only intertwine, overlap and occasionally interact on the legal and institutional level. The consideration of climate change under the UNCLOS is mostly interpretative. As ocean-relevant issues, they are under-represented in the consecutive treaties and on the climate agenda, although the vivid nature of climate negotiations does not exclude a greater emphasis in the future.

summit of June 1992 and came into force on March 21, 1994. It comprises 197 Parties in July 2019, including 196 States and the EU.

5 The PA on Climate (Annex of the decision 1/CP.21) was signed on December 10, 2015 and entered into force in a record time on November 4, 2016 (183 Parties in August 2019).

6 The UNFCCC was adopted in New York on May 9, 1992 (1171 UNTS 107). It was opened for signature at the Rio De Janeiro Earth summit of June 1992 and came into force on March 21, 1994. It comprises 197 Parties in July 2019, including 196 States and the EU.

CLIMATE CHANGE WITHIN THE OCEAN INTERNATIONAL LAW

The UNCLOS makes no explicit reference to climate change. Prima facie, the reduction of Greenhouse Gases (hereinafter GHG) to protect and preserve the marine environment falls outside its scope. The Convention shall nonetheless be interpreted and applied in good faith, considering any relevant rules of international law applicable in the relations between the parties, which encompasses the climate UN regime. In that respect, climate change has emerged in recent years beyond the UN climate regime and the fragmentation of international law, leading ocean specialists and policymakers to tackle this urgent challenge.

The interpretative consideration of certain aspects pertaining to climate change in the UNCLOS

The UNCLOS was negotiated during the third UN Conference on the Law of the Sea (1973-1982) at a time climate change was not on international environmental agenda. If the UNCLOS does not directly address climate change, it can be interpreted and applied to it, particularly through its provisions on "Protection and Preservation of the marine environment" (Part XII) and on "Marine Scientific Research" (Part XIII).

The Protection and the Preservation of the Marine Environment from climate impacts

The UNCLOS provides provisions enabling the conservation and enhancement of GHG sinks and reservoirs and, the protection of the marine environment from atmospheric pollution and degradation. This possible linkage operates through its provisions on the "protection and preservation of the marine environment" (Part XII). The conventional and customary obligation to protect and preserve the marine environment embedded in article 192 UNCLOS is relevant for climate change and potentially, GHG emissions impacting the marine realm and its biodiversity. This general obligation may apply to rare or fragile ecosystems like coral reefs, wetlands, vents and seamounts, as well as to habitats of depleted, threatened or endangered species and other marine life forms (Article 194(5)) affected by ocean acidification, deoxygenation or warming. It limits the States' right to exploit their natural resources (Article 193).

The obligation to protect and to preserve the marine environment is supplemented with other provisions tackling marine environment pollution. These provisions include general measures to prevent, reduce and control pollution from any source (art. 194), and specific measures such as measures to combat pollution from land-based sources (art. 207), pollution by dumping (art. 210), pollution from vessels (art. 211) and pollution from or through the atmosphere (art. 212). While dumping of wastes at sea, vessel-source oil and other pollutions have been controlled very effectively since the 1970s, land-based and atmospheric pollution of the marine environment have largely escaped regulation. Around 80% of pollution that entering the marine environment comes from land-based discharges and atmospheric sources.

Even if GHG are not specifically mentioned in UNCLOS as a source of pollution of the marine environment, the precautionary approach is applicable if there is evidence of a risk of serious or irreversible harm to the marine environment. It is also possible to interpret Part XII to include this type of pollution given the broad definition of marine pollution in article 1(1)4 and the indicative list of sources of pollution in article 194(3). The definition of marine pollution is significant as it provides criteria to determine a type of "substance or energy" is a marine pollution. It triggers the application of many pollution-related treaties. Not only GHG emissions from ships but a wide range of marine activities (mining extraction, shipping, etc.), as well as terrestrial activities (on land industrial activities, mining, deforestation, etc.) could possibly be covered, as sources of GHG, by the obligation of due diligence set in Article 194. Combined, Articles 194, 207 and 212 could cover all airborne sources of marine pollution comprehensively, including GHG. The relevant obligations of States can be inferred from the UNCLOS and underpins in a mutually supportive manner the UN climate change regime, the International Maritime Organization (hereinafter IMO) regime or the regional seas conventions and action plans[7].

The obligation for States and competent International Organizations to promote Marine Scientific Research, including on the ocean-climate nexus

The UNCLOS Part XIII on Marine Scientific Research (hereafter MSR) provides an innovative legal regime, governing scientific activities carried out by States and competent international organizations anywhere at sea. It includes, inter alia, provisions on the need to promote marine scientific research (art. 239) and international cooperation (art. 242), to create favorable conditions for MSR (Art. 243) and to circulate information and knowledge resulting from MSR by publication and dissemination (art. 244). Under these provisions and by means of synergetic cooperation, several national, regional and global research has been conducted in the marine realm with the aim of better understanding the impacts of climate change on the ocean and its biodiversity. For instance, the study of the ocean-atmosphere couple has been strengthened through ocean observing programs and geographic information systems, such as the Global Observation Observing System (GOOS) or the Global Sea Level Observing System (GLOSS). Ultimately, best available science has feed the decision-making process, and has invited States and non-state actors to develop sustainable and resilient ecosystem-based adaptation paths[8].

7 At regional Level, Regional Seas Programmes, traditionally focused on combatting marine pollution, were for a long time "underutilized" for cooperation between States and with regional fisheries management organizations (RFMOs) in addressing the adverse effects of climate change on the ocean. Among few constructive examples, the 2008 Protocol on Integrated Coastal Zone Management in the Mediterranean to the 1976 Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (in force since 2011) sets among its objectives the prevention and the reduction of natural hazards, and particularly climate change, which can be induced by natural or human activities (Art. 5 (e)). For more general information, D. Freestone, "Climate Change and the Oceans", Carbon & Climate Law Review, Vol. 3, No. 4, 2009, pp. 383-386; A. Boyle, "Law of the Sea perspectives on Climate change", The International Journal of Marine and Coastal Law, 27(4), 2012, pp. 831-838; J. Harrison, "Saving the Oceans through Law: The international Legal Framework for the protection of the Marine Environment", Oxford, Oxford University Press, 2017; S. Lee, L. Bautista, "Part XII of the United Nations convention on the Law of the Sea and the Duty to mitigate Against Climate Change: Making out a Claim, Causation, and Related Issues", Ecology Law Quaterly, Vol. 45- Issue 1, 2018, pp. 129- 156.

8 See, in particular, "The first global integrated marine assessment", under the auspices of the UN General Assembly and its Regular Process for Global Reporting and Assessment of the State of the Marine Environment, 2016, available online: https://www.un.org/regularprocess/content/first-world-ocean-assessment (last consulted July 2019); the UNESCO-IOC "Global Ocean Science Report: The Current Status of Ocean Science

Although the ocean science advances, there remain considerable knowledge, information, technological, financial, infrastructural and disciplinary gaps, as well as disparities amongst States. It can hamper the ability of policymakers to make informed decisions, even though ocean science plays a decisive and cross-cutting role in the achievement of the 2030 Agenda. As for the ocean and climate nexus, additional information is still needed in order to better understand sea temperature, sea level rise, salinity distribution, carbon dioxide absorption as well as nutrient distribution and cycling, many of which will be filled by the IPCC Special Report on "the Ocean and Cryosphere in Changing Climate" (SROCC) to be released in September 2019[9]. The forthcoming UN Decade of Ocean Science for Sustainable Development (2021-2030) carries with it the hope of opening the field of marine science to a more transdisciplinary approach, integrating human, social and legal scientists and stakeholders in the development of adaptive and reflexive socio-ecological solutions[10].

Climate change: an urgent challenge for ocean governance

The undebated evidence of the cumulative deleterious impacts of anthropogenic climate change on the marine environment (warming, sea-level rise, acidification, deoxygenation, disruption of ocean water masses and currents, loss of polar ice, biodiversity changes, release of methane, etc.), because of their geographic and temporal scales and complexity, as well as a lack of political will, have been slow to be translated into adaptive legal rules. It was only in the 2006 that climate change really started to be discussed by the ocean community and not only by some particularly vulnerable coastal and archipelagic States or active non state-actors[11]. Mitigation and adaptation challenges such as sea-level rise, ocean acidification, fisheries, GHG emissions from shipping, marine geo-engineering activities are still being discussed or even sometimes regulated within and beyond the ocean regulatory framework, without yet reaching a congruent programmatic vision. Two examples of well-advanced climate-related topics are given below.

The Sea-level rise: shifting maritime boundaries and likely disappearance of States

Besides threatening the integrity of marine ecosystems and environment, climate change threatens States' and population's integrity by the effect of sea-level rise caused by the melting of continental glaciers and polar caps and warming. Depending on the climate scenario, global mean sea level rise is projected to be between 30 cm and 1.10 m in 2100. The sea-level is not rising uniformly with significant local variations, with some areas experiencing three times the global average. More than 70 States are or are likely to be directly affected by sea-level rise, including many in low-lying least developed coastal States and small island developing States which are and will be flooded or submerged by seawater. Another quite large number of States is likely to be indirectly affected by the displacement of people or the lack of access to ressources.

Sea-level rise prompt several crucial questions relevant to international law and the Law of the Sea: possible legal effects of sea-level rise on the "shifting" baselines and outer limits of the maritime spaces measured from the baselines (territorial sea and contiguous zone, archipelagic waters, EEZ and continental shelf); on the status of natural or artificial islands and coastal States' maritime entitlements; on maritime delimitation between neighboring States; on maritime spaces under sovereignty and jurisdiction, especially regarding the exploration, exploitation and conservation of resources by

around the World", 2017, available online: https://en.unesco.org/gosr (last consulted July 2019), The IPBES "Global Assessment Report on Biodiversity and Ecosystem Services", May 2019, available online: https://www.ipbes.net/global-assessment-report-biodiversity-ecosystem-services (last consulted July 2019) and; the IPCC reports including the forthcoming special report (SROCC) on "The Ocean and Cryosphere in a changing Climate", available online: https://www.ipcc.ch/reports/ (last consulted in July 2019).

9 For more information, www.ipcc.ch/report/srocc (last consulted in July 2019).

10 For more information, https://en.unesco.org/ocean-decade (las consulted In September 2019).

11 See the two reports on the work of the United Nations open-ended informal Consultative process on the oceans and the Law of the Sea to the UN General Assembly on "The impacts of ocean acidification on the marine environment", A/68/159, July 17, 2013 and on "The effects of Climate change on the Oceans", A/72/95, June 16, 2017, available online: https://www.un.org/depts/los/consultative_process/consultative_process.htm (last consulted July 2019). In February 2019, The UNFCCC Secretariats joined UN-Oceans, the interagency mechanism on ocean and coastal issues with the UN System: see UN-Oceans 19th Session Report, Geneva, February 2019, available online: http://www.fao.org/fileadmin/user_upload/unoceans/docs/UN-Oceans19thMeetingReport.pdf (last consulted July 2019).

the Coastal States, as well as the rights of third States and their nationals (*e.g.*, innocent passage, freedom of navigation, fishing rights). In the most extreme cases, sea-level rise will mean the disappearance of coastal and low-lying islands which will be submerged or rendered uninhabitable. This raises the thorny political, moral and humanitarian issue of the possible loss of Statehood of archipelagic States and, the urgent need for protection of displaced persons which it entails.

Legal solutions are being discussed by legal scholars or have already been put in place to address these challenges: the reinforcement of coasts and islands with barriers or the erection of artificial islands as a means to preserve the statehood of island States against risks of submersion, erosion or salinization of freshwater reserves; the transfer, with or without sovereignty, of a portion of territory of a third State, as in the case of Kiribati purchasing land in Fiji or Tuvalu in New Zealand and Australia; the creation of a legal fiction of the statehood's continuity of islands States, by freezing baselines and/or outer limits as legally established before islands states were submerged or uninhabitable or; the creation of federations of association between small island developing States and other States to maintain the former statehood or any form of international legal personality[12].

The regulation of GHG emissions from ships

Considering the importance of maritime transport (about 90% of trade is carried out on the oceans and seas) and its GHG emissions accounting for roughly 2.2% of total carbon emissions, control and reduction of GHG emissions from international shipping are a major challenge for ocean governance. Most of the GHG emissions from ships are emitted in or transported to the marine boundary layer where they affect atmospheric composition. In general, the link between the UNFCCC bodies and COP and, the IMO is more co-operative than conflictive. Co-operation with the IMO (174 Member States and 3 associate members) has become a regular agenda item of the UNFCCC Subsidiary Body for Scientific and Technological Advice (hereinafter SBSTA), under which the IMO reports its progress in accordance with the climate law objectives. The IMO was and still is a catalyst for co-operation, even if the negotiations on GHG emissions reduction have been shaped by tensions between developed and developing States.

Shortly before the Kyoto conference, the Conference of Parties to the 1973/78 convention for the Prevention of Marine Pollution (hereinafter MARPOL) adopted on 26 September 1997 a new Annex VI on "Regulations for the Prevention of Air pollution from Ships", setting out modest non-mandatory standards to reduce air pollution from all ships, with emphasis on Sulphur Oxide (SOx) and nitrogen oxide (NOx). Following the entry into force of Annex VI on 19 May 2005, the Marine Environment Protection Committee (MEPC) agreed to revise MARPOL Annex VI with the aim of significantly strengthening the emission limits via technological improvements and implementation experience. After three years of examination, the MEPC adopted the revised MARPOL Annex VI and the associated NOx Technical Code in October 2008, which both entered into force on 1 July 2010. Contracting Parties to Annex IV has increased rapidly (from 91 in July 2018 to 143 a year later), including the States accounting for almost all global tonnage.

In July 2011, the MEPC 62 adopted the first mandatory global GHG reduction regime for an entire industry sector and the first legally binding agreement instrument to be adopted since the KP, which entered into force on 1st January, 2013, applicable to all ships navigating under the flag of States Parties. It adds to MARPOL Annex VI a new Chapter 4 entitled "Regulations on energy efficiency for ships", which makes the Energy Efficiency Design Index (EEDI) mandatory for new ships

12 These solutions, already studied by the International Law Association since 2012, will be the subject of a future report by the International Law Commission on "Sea-Level Rise in relation to International Law" as recommended in decision A/73/10 of 2018, available online: http://legal.un.org/ilc/guide/8_9.shtml (last consulted July 2019). For more information: D. Vidas, "Sea-Level Rise and International Law: At the Convergence of Two Epochs", 2014, Climate Law, 4, pp. 70-84; C. Schofield and A. Arsana, Climate change and the limits of maritime jurisdiction, in R. Warner, C. Schofield (ed.), "Climate Change and the Oceans: Gauging the Legal and Policy Currents in the Asia Pacific and Beyond", Cheltenham, UK/ Northampton, MA, USA, Edward Elgar, 2012, p. 127-152; J. G. Xue, Climate Change and the Law of the Sea: Challenges of the Sea Level Rise and the Protection of the Affected States, in K. Zou (ed.), "Sustainable Development and the Law of the Sea", Leiden/Boston, Nijhoff-Brill, 2016, pp. 243-277; K. N. Scott, "Climate Change and the Oceans: Navigating Legal Orders", in M. H. Nordquist, J. N. Moore, R. Long (ed.), Legal order in the World's Oceans: UN Convention on the Law of the Sea, 2017, Leiden/Boston, Brill-Nijhoff, pp. 124-164.

and the Ship Energy Efficiency Plan (SEEMP) for all ships over 400 gross tonnage. It requires ships to be constructed according to a design, named Energy Efficiency Design index (EEDI), which sets a minimum energy-efficiency level for different ship types and sizes. In October 2016, the MEPC 70 approved a Roadmap for developing a comprehensive IMO strategy on reduction of GHG emissions from ships, which provides for an initial GHG reduction strategy to be adopted in 2018 and a revised Strategy by 2030.

In May 2019, MEPC 74 progressed in the implementation of its initial strategy by, among others, planning to amend MARPOL Annex VI at MEPC 75 in April 2020 to strengthen the existing EEDI for some categories of new ships forward from 2025 to 2022 with lower emission reduction targets, adopting a resolution on "Invitation to Member States to encourage voluntary cooperation between the port and shipping sectors to contribute to reducing GHG emissions from ships" and, approving a "Procedure for assessing impacts on States of candidate measures for reduction of GHG emissions from ships".

Despite these measures, an increase of shipping's GHG emissions of 50-250% is foreseen by 2050. The impacts of EEDI on reduction of shipping emissions are estimated to be small. Since the EEDI regulation affects only new build ships, most of ships will not be covered by EEDI before 2040. Furthermore, GHG emissions are not the only aspect of shipping which may affect marine environment. The use of high-density fuel oil in or near the Arctic Ocean produces harmful and significantly higher emissions of Sulphur oxide (SOx) and nitrogen oxide (NOx) that contribute to accelerated snow and ice melt. More generally, although the amendments to Annex VI will have a relatively small impact in controlling global GHG emissions. To avoid emissions "leakage" and be synergetic, GHG reduction efforts from shipping must be correlated with reduction efforts in aviation and land transportation and beyond, with technology, operations and alternative energy sectors[13].

OCEAN WITHIN THE CLIMATE INTERNATIONAL LAW

In a disconcerting trompe-l'oeil effect, the realistic legal imagery of the climate international law creates the forced illusion that the ocean does not appear to be relevant to climate change or at least, only as a background image in climate negotiations and treaties. This is not so much due to the absence of the ocean in the UN climate regime, but to the lack of overall treatment and effectiveness of the specific legal provisions applicable to it. The ocean is marginally considered by the UNFCCC and the KP, whereas the extent to which the PA is applicable to it remains progressive and therefore, uncertain in its legal effect. However, the vivid nature of climate negotiations probably foresees a greater emphasis of ocean-related issues in the future.

The trompe l'oeil view of the ocean in the UNFCCC and the KP

The preamble (recital 4) of the UNFCCC expressively refers to the role and importance of sinks and reservoirs of GHG in marine ecosystems. Article 4 (1) d) states that all Parties, "[…] shall promote sustainable management, and promote and cooperate in the conservation and enhancement, as appropriate, of sinks and reservoirs of all greenhouse gases not controlled by the Montreal Protocol, including […] oceans as well as other […] coastal and marine ecosystems". The UNFCCC apprehends the ocean through this "narrow but significant prism"[14]. As for measures related to "integrated plans for coastal zone management" (Art. 4 (1) e)) or the possible adverse effects of sea-level rise on islands and coastal areas (Preamble, recital 12), they are equally vague because adaptation was originally not clearly or only theoretically defined in the UN climate regime.

13 For more information, D. Bodansky, "Regulating Greenhouse Gas emissions from Ships: The Role of the International Maritime Organization", in H. Scheiber, N. Oral and M. Kwon (eds.), Ocean Law Debates: The 50-Year Legacy and Emerging Issues for the Years Ahead, Leiden/Boston, Brill-Nijhoff, 2018, pp. 478-501; A. Chircop, M. Doelle and R. Gauvin, "Shipping and Climate Change International Law and Policy Considerations", Special Report of the Center for International Governance Innovation, 2018, 92 p., available online: https://www.cigionline.org/sites/default/files/documents/Shipping%27s%20contribution%20to%20climate%20change%202018web_0.pdf (last consulted July 2019).

14 B. Guilloux, R. Schumm, "Which international Law for Ocean and climate?", Ocean & Climate platform Scientific Note, 2016, p. 84, available online: https://youthforocean.files.wordpress.com/2017/06/161026_scientificnotes_guilloux.pdf (last consulted July 2019).

In the KP, the ocean remains marginally considered. The only notable provision concerns the reduction in GHG from maritime transport sector. Article 2(2) of the KP provides that "the Parties which accounted in total for at least 55 % of the total carbon dioxide emissions for 1990 (Annex I) shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol […] from marine bunker fuels, working through […] the International Maritime Organization", mandating this specialized UN organization to take more specific mitigation measures in this sectoral area. To track these measures, the IMO Secretariat is regularly reporting to the UNFCCC subsidiary Body for Scientific and Technological Advice (SBSTA) under the agenda item on "emissions from fuel used for international aviation and maritime transport" and participate in UN system activities including side events parallel to COP-MOP-CMA.

In both treaties, the extent to which the ocean and the marine ecosystems can be conserved and enhanced as GHG sinks and reservoirs to mitigate anthropogenic climate change remains vague, without further detailed provisions or reference to the UNCLOS or other relevant agreements. This can partially be explained by the broad scope of the UNFCCC and the fact that the UN climate negotiations has traditionally focused on land based GHG emissions in the atmosphere. If States have however been encouraged to protect and enhance sinks and reservoirs of GHG, only terrestrial sinks or considered as such like mangroves have been utilized by States to meet the emission targets[15]. Ocean sinks, which are nevertheless the most important climate mitigator, remain mostly ignored because they are naturally occurring, rather than directly attributable to human activities.

A progressive consideration of the Ocean within the PA framework

The PA is built up on the 2009 Copenhagen (minimalist) Accord[16] and the 2010 Cancun Agreements[17]. It broadens the UN climate regime to encompass the GHG emissions of emerging economies such as China, India and Brazil. Contrary to the internationally negotiated and legally binding emissions targets of the KP, it involves a bottom-up process in which States make Nationally Determined Contributions (NDCs), specifying their plan to limit their domestic emissions (Art. 3) vis-à-vis the temperature limitation goals set for all States in Article 2[18].

The inclusion of a reference to the ocean in the preamble of the PA acknowledges a renewal of how the ocean is considered by the Climate law, since it is explicitly mentioned as such, albeit only in general terms and in non-operative part: "noting the importance of ensuring the integrity of all ecosystems, including oceans, and the protection of biodiversity, recognized by some cultures as Mother Earth […]" (Preamble, Recital 13). This Recital responds to a long-standing concern that marine biodiversity and ecosystem integrity risks are not sufficiently considered by Parties when taking climate action. Such a clause can assume a function of integration and of conflict avoidance with the ocean international law. Although essentially symbolic and political, its legal effect is linked to the universal scope of and the twilight legal effect on the PA itself.

The PA also gives adaptation prominence, which is an important dimension of climate action for several biodiversity, fishery and regional seas instruments. Parties recognize that adaptation is a multiscale global challenge and a key component of the long-term global response to climate change to protect people, livelihoods and ecosystems, particularly in vulnerable developing countries (Art. 7). Therefore, it can serve as a potential common denominator to improve legal and political synergies between ocean and climate regimes. Like the UNFCCC and the KP, the PA remains elusive about ocean-related issues, both in terms of mitigation and adaptation[19]. This lack of considera-

15 Hence blue carbon coastal ecosystems have not become a new climate mitigation and co-beneficial adaptation option under the UN climate regime, but they have been partially included in existing market-based mechanisms. For example, mangroves only are eligible under The UN collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation (REDD+).

16 Decision 2/CP.15.

17 COP 16/CMP 6.

18 The Agreement provides for emission reduction commitments for all States, "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (Article 2 (1) (a)).

19 rticle 5(1) specifically emphasizes the role of forests in conserving and enhancing GHG sinks and reservoirs. The ocean

tion must not appear to foreshadow a disappointing legal future, insofar as the implementation of the PA is based on a progressive bottom-up approach[20].

Towards a greater emphasis on the ocean in the climate regime?

In implementing the PA, States have significant capacity to enhance synergies between the ocean and climate regimes (and avoid conflicts) by adopting congruent NDCs and, by providing incentives for domestic actors to change their behavior in order to contribute to both climate and ocean regimes' objectives. At International level, it is likely that the ocean will be discussed in formal negotiations, if not as a separate topic, at least in relation to adaptation action.

Valuing the role of Ocean in Nationally Determined Contributions (hereinafter NDCs)

Rather than setting binding targets within the PA itself, all Parties define independently these targets to the global response to climate change within their NDCs, which cover the efforts made by each of them to reduce national GHG emissions and to adapt to the adverse effects of climate change (Art. 4). Article 3 set a general obligation of conduct, *i.e.* to undertake and communicate NDCs of increasing ambition, whereas the overarching temperature goal of Article 2 is an obligation of result[21].

In July 2019, 6183 States and the European Union have submitted a NDC on the dedicated UNFCCC platform, representing all Parties to the PA[22]. Many contributions are based on national circumstances, address all national major or most significant sources and sinks of GHG emissions and, include an adaptation component. In framing their NDCs, States have significant capacity to enhance synergies between the ocean and climate regimes (and avoid conflicts) by adopting congruent mitigation and adaption policies, and by providing incentives for domestic actors to change their behaviour in order to contribute to both climate and ocean regimes' objectives. Out of 146 coastal or archipelagic States Parties to the PA which have submitted adetermined contribution, 82 have expressively identified key issues relating to the ocean in the context of mitigation or adaptation, among which about 60 of them have established a clear linkage with SDG 14 (Life below Water). 16 other States mention the ocean ina very superficial or only to describe their geographical context. Together, they represent approximatively 67% of the total of NDCs registered in 2019. 49 coastal and archipelagic States do not refer to the ocean or ocean-related subject matters (*e.g.* fisheries, coastal ecosystems, sea-level rise) at all, including some with very large marine areas such as USA, Australia and the Russian Federation. Surprisingly, some States which do not address ocean-related actions in their NDCs (for *e.g.* Monaco or Norway) are very active on the international scene. The Annex I countries remain systematically focused on climate change as more a problem of mitigating emissions and neglect the ocean (for *e.g.* the EU member States), which demonstrate a caesura among developed States between ocean and climate regimes. On the contrary, SIDS and African countries, particularly vulnerable to climate change and lacking capacity, show a will of interaction between ocean and climate regimes through ocean-based adaptation measures related to fisheries (42 NDCs), coastal protection (54 NDCS) or the preservation of marine ecosystems (for *e.g.* Benin and Guinea Bissau). These

is not explicitly mentioned which indicates that it is not a priority focus. Moreover, no further reference to the IMO is made in either the PA, nor the decisions to implement the Agreement, including the pre-2020 ambition and action.

20 For further information, see S. Lavallée, S. Maljean-Dubois, « L'accord de Paris : Fin de la crise du multilatéralisme climatique ou évolution en clair-obscur ? », 2016, RJE,pp. 19-36 ; R. Clémençon, "The Two Sides of the Paris Climate Agreement: Dismal Failure or Historic Breakthrough?", 2016, Journal of Environment & Development, Vol. 25(1), pp. 3-24; D. Klein, M.P. Carazo, M. Doelle, J. Bulmer and A. Higham, "The Paris Agreement on Climate change: Analysis and commentary", Oxford, 2017; D. Bodansky, J. Brunnée and L. Rajamini, "International climate Change Law", Oxford, 2017; R.J. Salawitch, T.P. Canty, A.P. Hope, W.R. Tribett, B. F. Benett, "Paris Climate Agreement: Beacon of Hope", Springer, 2017; S. Oberthür, R. Bodle, "Legal Form and Nature of the Paris Outcome", 2016, Climate Law, Vol. 6, pp. 40-57; M. Torre-Schaub, (dir.), « Bilan et perspectives de l'Accord de Paris (COP 21) : regards croisés, IRJS, 2017.

21 J. Pickering, J. S. McGee, S. I. Karlsson-Vinkhuyzen and J. Wenta, "Global Climate Governance Between Hard and Soft Law: Can the Paris Agreement's 'Crème brûlée' Approach Enhance Ecological Reflexivity?", Journal of Environmental Law, 2019, Vol. 31, pp. 1-28; L. Rajamani, "The 2015 Paris agreement: Interplay between hard, soft and non-obligations", Journal of Environmental Law, 2016, Vol. 28, pp. 337-358; N. Höhne, T. Kuramochi, C. Warnecke, F. Röser, H. Fekete, M. Hagemann, T. Day, R. Tewari, M. Kurdziel, S. Sterl and S. Gonzales, "The Paris Agreement: resolving the inconsistency between global goals and national contributions", 2017, Climate Policy, Vol. 17(1), pp. 16-32.

22 NDC Registry (interim): https://www4.unfccc.int/sites/ndcstaging/Pages/Home.aspx.

expressions of will and concern are still struggling to be transformed into an operative action framing due to a lack of information and capacity. Certain impacts such as ocean acidification (14 NDCs) receive little attention from governments because the lack of knowledge and education and 39 NDCs include information on additional marine research needs[23].

NDCs are a mean for Parties to adjust to national circumstances and particularities which is of great relevance for ocean-based adaption and mitigation. But they also bear the risk of a belayed and insufficient implementation of Article 2 or of disorderly pluralism[24]. It will be therefore necessary to monitor the cost-effectiveness and implementation of ocean-based mitigation and adaptation national measures in a changing climate and environment. Finally, whilst indicating the will of certain States, particularly developing States, to tackle ocean and climate-related issues in a coordinated or integrated manner, NDCs are not the only indication of government's investment in ocean and climate-related actions and other pathways of interactions could be followed.

"Oceanizing" the climate negotiations

During the period from 1992 to 2015, it appeared that climate treaty bodies have been rather passive on the relationship with the ocean regime, which may be surprising given the potential for conflicts or synergies. National delegates generally demonstrated a lack of political will to put ocean related issues on the political agenda or, to develop any ocean-related strategy, because this will bring highly contested issues among State Parties, such as funding or technology transfer.

It was only at COP 21 that some already active groups of States (SIDS and the Alliance of Small Islands States (AOSIS)) or, more eclectic alliance of developed and developing States along with non-state actors, initiated actions to raise awareness of climate risk in oceans and coastal areas, to influence the outcomes of Climate COP and, to foster ocean and climate regime interactions. Following the request made by governments to the IPCC to prepare a Special Report on "the Ocean and Cryosphere in Changing Climate" (SROCC)[25], such mainstreaming gained in intensity. It resulted in recurrent dedicated "Ocean days" and ocean-related side-events alongside official climate negotiations and, the formulation of programmatic orientations, including the "Roadmap to Oceans and Climate Action" (ROCA)[26], the "Because the ocean" initiative[27] and, the "Ocean pathway towards an Ocean inclusive UNFCCC process"[28].

In the wake of SROCC findings which will be disclosed in September 2019, the COP 25 (co-hosted by Chile and Costa Rica), envisioned by the Chilean president as the "Blue COP"[29], could serve as a political momentum to address ocean and climate nexus in a more integrated manner. As the climate change has "climatized" the global political debates[30], the ocean could "oceanize" climate negotiations by gaining traction, even among unilateralist countries (*e.g.* Australia, Japan or the USA) and, seeking an ocean-specific UNFCCC COP agenda item and/or a SBSTA entry point. If not tackled as a separate topic, the ocean will be however correlated to adaptation. Oceans, coastal areas and ecosystems, including mega deltas, coral reefs and mangroves, will be addressed within the Nairobi work programme on impacts, vulnerability and adaptation to climate change (NWP)[31].

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23 N. D. Gallo, D.G. Victor, L.A. Levin, "Ocean Commitments under the Paris Agreement", Nature Climate Change, vol. 7 (November 2017): 837.

24 Compared with the emission levels under least-cost 2°C scenarios, aggregate GHG emission levels resulting from the implementation of the INDCs in 2016 were expected to be higher by 19% in 2025 and 36% in 2030: Doc. FCCC/CP/2016/2 (2 May 2016), pp. 10-11. On the effects of disorderly pluralism in International Law, see M. Delmas-Marty, Les forces imaginantes du droit (II) : Le pluralisme ordonné (Paris : Seuil, 2006), 303 p.

25 The decision to prepare a SROCC was made at the Forty-Third Session of the IPCC in Nairobi (Kenya, 11-13 April 2016): "Decision IPCC/XLIII-6. Sixth Assessment Report (AR6) Products. Special Reports", para. 4, p. 11: https://archive.ipcc.ch/meetings/session43/p43_decisions.pdf. The SROCC is under the joint scientific leadership of Working Groups I, II and III with support from the WGII TSU.

26 For more information, https://roca-initiative.com/ (last consulted July 2019).

27 For more information, https://www.becausetheocean.org/ (last consulted July 2019).

28 For more information, https://cop23.com.fj/the-ocean-pathway/ (last consulted July 2019).

29 C. Schmidt, "Before the Blue COP", opening speech, Because the Ocean Imitative Workshop, Madrid, April 10, 2019, available online: https://www.becausetheocean.org/before-the-blue-cop-madrid-workshop-opens/ (last consulted in July 2019).

30 See S. Aykut, J. Foyer, E. Morena, "Globalising the Climate: COP 21 and the climatization of global debates", Routledge, 2017.

31 Doc. FCCC/SBSTA/2019/INF.1 (11 June 2019), para. 30 and 31.

CONCLUSION

The question of whether Ocean and Climate International Laws will be able to face in a congruent way new challenges posed by climate change on the ocean (and vice versa) remain open. For now, their responses lack of regime interactions, as well as synergies between mitigation and adaptation measures and across time and temporal scales. Throughout global, regional, sectoral and national laws and policies, mitigation and adaptation are often treated separately. Adaptive Law could help to reflect the diversity of socio-ecological contexts, reconcile the enhancement of the ocean and marine ecosystems as sinks of GHG with their conservation, in accordance with the precautionary principle and an integrated management. Such a dynamic and resilient approach based on transdisciplinary governance could foster synergies between separate management approaches (climate change mitigation and adaptation, marine pollution, biodiversity conservation, fisheries) and fragmented regimes (ocean, climate and biodiversity regimes).

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