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SCIENTIFIC ITEMS

PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

Why an "Ocean and Climate" platform ?

The ocean is a key element of the global climate system, but so far it has been relatively absent from discussions on climate change. For all of us participating in the Ocean and Climate Platform, it is essential to include the ocean among the issues and challenges discussed in the context of climate negociations.

Covering 71 % of the globe, the world ocean is a complex ecosystem that provides essential services for the maintenance of life on Earth. More than 25 % of the CO_2 emitted annually by humans into the atmosphere is absorbed by the ocean, and it is also the largest net supplier of oxygen in the world, playing an equally important role as the forests.

The ocean is therefore the principle "lung" of the planet and is at the center of the global climate system.

Although the ocean continues to limit global warming, for several decades the pressure of human beings -- principally CO_2 emissions, over-exploitation of resources and pollution have degraded marine ecosystems. The role of the ocean in regulating the climate is likely to be disrupted.

It is therefore urgent to maintain the functional quality of marine ecosystems and restore those that are becoming degraded.

The Ocean and Climate Platform was established from an alliance of non-governmental organizations and research institutes, with support from the UNESCO Intergovernmental Oceanographic Commission.

Today the Platform includes scientific organizations, universities, research institutions, non-profit associations, foundations, science centers, public institutions and business organizations, all acting to bring the ocean to the forefront in climate discussions.

Our objectives

In December 2015 in Paris the 21st United Nations Climate Conference will take place. This conference will establish the roadmap that will enable the international community to meet the challenges of climate change in the coming years. The Ocean and Climate Platform aims to :

INTEGRATE THE OCEAN IN THE DEBATE ON CLIMATE, AND CONTRIBUTE TO SUCCESSFUL NEGOTIATIONS FOR AN AMBITIOUS AGREEMENT AT THE COP21

The Paris Agreement must take into account the ocean and its role in the climate to best confront the major climate challenges in the years to come.

INCREASE PUBLIC AWARENESS ABOUT THE IMPORTANCE OF THE OCEAN IN THE GLOBAL CLIMATE SYSTEM

Advancing the general public's knowledge about the links between the climate with ocean and coastal areas will contribute to a better understanding and consideration of the impacts of climate change on the marine environment.

PROMOTE SCIENTIFIC KNOWLEDGE ABOUT THE LINKS BETWEEN OCEAN AND CLIMATE

The links between ocean and climate are gradually becoming better defined, but the needs for knowledge and research are still very important. Having a set of indicators will allow us to better monitor the evolution of the ocean within the climate system.

INFORM AND INSTRUCT PUBLIC AND PRIVATE POLICY MAKERS ON OCEAN AND CLIMATE ISSUES

Policy makers at all levels – heads of state, representatives of international organizations and national governments, private actors – have too little knowledge about the role of the ocean in climate. The issues related to the impacts of climate change on marine and terrestrial ecosystems of the coast (where nearly 80 % of the world population will concentrate in 2050) must be clearly identified.

FOR FURTHER INFORMATION, PLEASE CONTACT:

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Foreword

Françoise Gaill
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The importance of the ocean in climate change negotiations has been considered only until very recently. The following texts point to a change in mindset. They show that this planetary environment has at long last been given its rightful place in climate issues. Concerns such as the role that the ocean plays for the climate and the impacts of climate change on the ocean are addressed in this document.

The climate of our planet is largely dependent upon the ocean, but who is aware of this nowadays?

The ocean regulates the climate at a global scale due to its continuous exchanges with the atmosphere, whether they are radiative, mechanical or gaseous. The heat from the sun is absorbed, stored and transported by the ocean, thus affecting the atmospheric temperature and circulation. Although its ability to store heat is much more efficient than that of the continents or the atmosphere, the limits of this storage capacity are still unknown.

Marine waters are warming up, thus impacting the properties and dynamics of the ocean, the interactions with the atmosphere, and the marine ecosystems and habitats. Coral reefs, for example, cover a small area of the ocean, but they shelter close to a third of known marine species. An increase of less than a degree beyond a given threshold may cause bleaching and potential loss of a reef. The consequences are significant because these bioconstructions provide many services including a direct source of livelihood for more than 500 million people worldwide.

It is not sufficiently acknowledged that each day, the ocean absorbs a quarter of the CO_2 produced by humankind. This is followed by a chemical modification of the sea water which results in the acidification of the ocean. Ocean acidity has increased by 30% over two and a half centuries and this phenomenon continues to amplify, thus directly threatening marine species.

Indeed, the ocean is clearly a carbon sink, as it can concentrate fifty times more carbon than the atmosphere. Both physical and biological mechanisms contribute to the absorption and storage of oceanic carbon, the planktonic ecosystem being the main contributor to the biological pump. Although this biological carbon pump has been identified, the scope of its action still remains to be determined. It is worth noting that marine biodiversity only represents 13% of all described living species on Earth. This is particularly low, considering the colossal volume of the ocean. The future should tell whether this is related to a lack of knowledge. Nonetheless, the still unknown domain of the deep ocean may provide an answer once it is explored, as this deep environment represents more than 98% of the volume of the ocean. The ocean is often seen as a stable and homogeneous environment, with low biological activity, covering vast desert areas. This does not truly reflect the diversity of deep-sea ecosystems, neither their sensitivity to climate change.

With increasing seawater temperature, the ocean expands and sea level rises. This is even faster when ice melt accelerates. Numerical models forecast an increase by more than a quarter of a meter by the end of this century with a maximum greater than 80 cm. The causes and variability of this phenomenon are questions that are addressed in this booklet which also presents examples of the socio-economic outcomes for small islands, aquaculture and exploited living resources.

Everything cannot be assessed here, and new documents will progressively complete the set of topics that we believe are relevant, such as issues related to the anoxia of marine waters, to the Arctic and polar regions, to coastal waters which have only been discussed here for island environments, and more generally to the vulnerabilities related to oceanic phenomena. On the basis of these syntheses focused on specific areas, progress can be achieved in the development of possible solutions, strategies and concrete proposals.

What do we know about these processes at "human" space-time scales, annual or decennial, regional or local scales? Actually, not much is known because these data are currently not available. For the moment, only long geological periods, and vast areas, have been assessed. Moreover, given the spatial diversity, the small-scale mechanisms at work cannot yet be clearly deciphered. This is particularly the case for thermal variations, carbon uptake mechanisms, sea level changes, impact of acidification on marine ecosystems as well as the interactions between these different factors. To which extent can life adapt today, whether considering natural species or those exploited by fisheries or produced by aquaculture? Furthermore, how will tomorrow's ecosystems cope with these changes? Observations relative to these phenomena need to be carried out in order to understand the overall mechanisms and to infer the outcomes for our civilization, in the perspective of both ecosystem services as well as socio-economic consequences.

Can the characteristics of the global ocean be averaged in a reasonable manner? In order to assess the dynamics of the ocean ecosystem in response to the combined effects of natural, climatic and anthropogenic instabilities in different parts of the ocean, the couplings between climate fluctuations and stability of ecological functions need to be described; this highlights a few research topics for scientists in the future.
These texts intend to draw public attention towards questions raised upon what is known about climate change, but also to highlight issues that still remain unsure. Indeed, facing climate change, the ocean still acts as a shield upon which the future of our planet greatly depends.

Ocean, Heat Reservoir

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On our watery planet, the ocean is the primary regulator of global climate by continuous radiative, mechanical and gaseous exchanges with the atmosphere. In particular, the ocean absorbs, stores, and transports through its flow motion (*i.e.*, currents) heat from the sun affecting atmospheric temperature and circulation around the world. Furthermore, seawater is the source of most precipitation. The ocean is way much more efficient at storing heat (93% of the excess of energy resulting from the human induced Green House Gases content in the atmosphere) than the continents (3%) and the atmosphere (1%). The upshot of this is that the ocean is the slow component of the climate system and has a moderating effect on climate changes. However, consequent to the continuous absorption by the ocean of the human induced excess of heat, ocean waters are warming, which has consequences on the ocean's properties and dynamics, on its exchanges with the atmosphere and on the habitats of marine ecosystems. For a long time, discussions of climate change did not take the oceans fully into account, simply because very little was known about them. To a considerable degree our ability to understand and anticipate what might happen to Earth's climate in the future, depends on our understanding of the role of the ocean in climate.

OCEAN - HEAT RESERVOIR

Our Earth is the only known planet where water exists in three forms (liquid, gas, solid), and in particular as liquid oceanic water. Due to its high heat capacity, radiative properties (gaseous) and phase changes, the presence of water is largely responsible both for our planet's mild climate as well as to the development of land life.

The oceans represent 71% of the surface of the planet. They are so vast that one can easily underestimate their role in the earth climate. The ocean is both a large reservoir, but at the same time continuously contributes to radiative, physical and gaseous exchanges with the atmosphere. These transfers and their impacts on the atmosphere and the ocean are at the core of the climate system.

The ocean receives heat from solar electromagnetic radiation, in particular in the tropics. It exchanges heat at its interface with the atmosphere at all latitudes, and with sea-ice in polar regions. The ocean is not a static environment: ocean currents are responsible for the redistribution of excess heat received at the equator towards the higher latitudes. At these latitudes transfers of water from the surface to the deep ocean take place as water loose buoyancy flowing poleward due to the effect of strong heat loss. The mechanism of this vertical dense water transfer related to an increase of sea-water density (caused by a lowering of the temperature or an increasing of salinity) is the starting point for the global ocean thermohaline circulation (derived from the Greek therme: heat; halos: sea salt). The ocean also reacts dynamically to changing climatic conditions (*i.e.* wind, solar radiation…). The time scale of these processes can vary from a seasonal or yearly scale in tropical areas to a decadal scale in surface waters, reaching several hundreds, even thousands of years in the deep ocean layers.

The atmosphere and ocean do not only exchange heat: water is also exchanged through the processes of evaporation and precipitation (rain, snow). The oceans contain 97.5% of the water on the planet, while continents contain 2.4% and the atmosphere less than 0.001%. Water evaporates virtually continuously from the ocean. Rain and river runoff compensate for evaporation, but not necessarily in the same regions as evaporation. Furthermore, the salt content in the ocean modifies the physical properties of seawater, particularly its density. Water exchange with the atmosphere, riverine input and melting of sea ice and ice caps thus contribute to variations in the density of sea water, and hence to the ocean circulation and vertical transfers within the ocean.

In addition, thanks to ocean circulation, the renewal of surface water, and in particular the exchanges with the deep ocean layers, play a very important role in carbon cycling as high latitude CO_2 enriched waters are drawn down towards the deep ocean.

THE TEMPERATURE OF THE OCEAN IS RISING

Recent warming caused by the emission of greenhouse gases related to human activity does not only affect the lower layers of the atmosphere and the surface of the continents. Measurements of sea temperature have been made during the past five to six decades over the 1000 to 2000 first meters of the ocean from ships, oceanographic buoys, moorings and more recently, autonomous profiling floats (the Argo project) that enable vertical sampling of the top 2000 m of the water column. They have allowed oceanographers to observe a significant increase in the temperature of the ocean over the studied period. On first hand, this recent warming of the ocean affects the surface layers (the first 300 to 500 meters). However at high

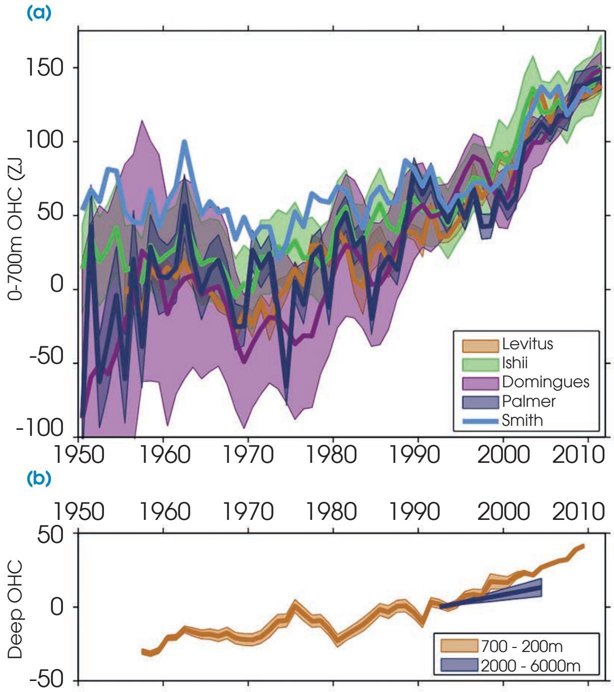

Fig.1— **(a)** Evaluation of the yearly average of the heat content in ZJ (1 ZJ = 10^{21} Joules) calculated from observations in the surface layers of the ocean (between 0 and 700m depth). these estimates have been updated from Levitus *et al.* (2012), Ishii and Kimoto (2009), Domingues *et al.* (2008), Palmer *et al.* (2007) and Smith and Murphy (2007). Uncertainties are in grey, as has been published in the different aforementioned studies. **(b)** Estimates of the moving average of the heat content in ZJ over 5 years for the 700 to 2000m layer (Levitus 2012) and for the deep ocean (from 2000 to 6000m) during the 1992 to 2005 period (Purkey and Johnson, 2010). Figure adapted from Rhein *et al.*, 2013.

latitudes, the temperature increase has reached the deep layers of the ocean (Figure 1; Rhein *et al.*, 2013; Levitus *et al.*, 2012; Ishii and Kimoto, 2009; Domingues *et al.* 2008; Palmer *et al.*, 2007; and Smith and Murphy, 2007).

The temperature of the 0-300m layer has increased by about 0.3°C since 1950. This value is approximately half than the temperature increase at the surface of the ocean. Furthermore, although the average temperature of the ocean has increased less than that of the atmosphere, the ocean represents the greatest sink and reservoir of excess heat introduced into the climate system by human activities. This is due to its mass as well as its high thermal capacity. Indeed, over 90% of the excess heat due to anthropogenic warming accumulated in the climate system during the past 50 years has been absorbed by the ocean (15 to 20 times higher than observed in the lower atmosphere and on land; Figure 2). This represents an excess energy storage by the ocean that is greater than 200 zeta-joules (2 • J 10^{23}; 1ZJ = 10^{21}Joules) since the 1970s.

Recent results also show that the deep ocean has actually accumulated a larger amount of heat than had been estimated so far, which may explain, simultaneously with the impact of natural

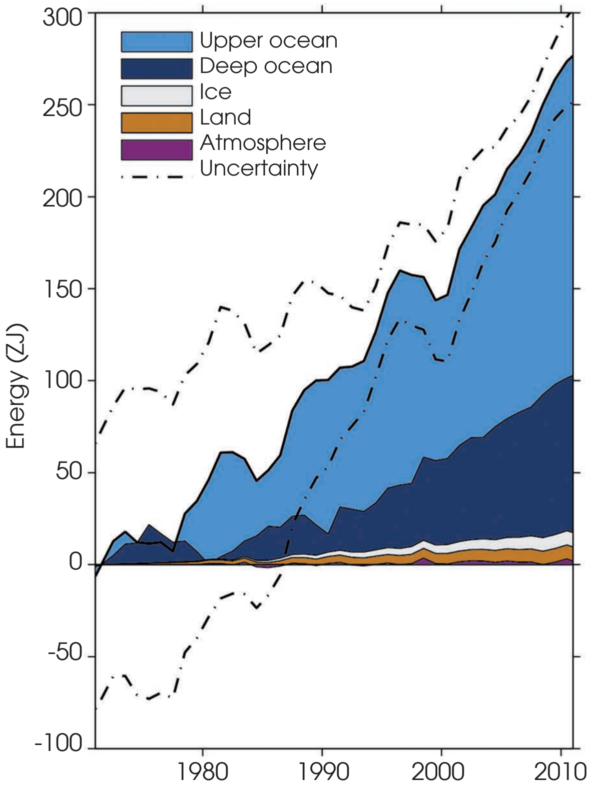

Fig.2— Energy accumulation curve in ZJ with reference to the year 1971 and calculated between 1971 and 2010 for the different components of the global climate system. The sea temperature rise (expressed here as a change in heat content) is significant. The surface layers (light blue, 0 to 700m deep) contribute predominantly, while the deep ocean (dark blue; water layers below 700m) is also a significant contributor. The importance of the role of the melting of continental ice (light grey), the continental areas (orange) and the atmosphere (purple) is much smaller. The broken line represents the uncertainty of estimates. Figure adapted from Rhein *et al.*, 2014.

climate variability such as the El Nino Southern Oscillation (ENSO), the recently observed slow-down in atmospheric warming (Durack *et al.*, 2014). This excess heat in the ocean is caused by direct warming from solar energy (*e.g.*, this is the case in the Arctic due to an intensified reduction in the area of sea ice during summer) as well as thermal exchange enhanced by increasing infrared radiation due to rising concentrations of greenhouse gases in the atmosphere. The continuing or even increasing accumulation of heat in the deep layers explains that the ocean heat content kept rising during the last ten years, despite near-constant average surface ocean temperature (Balmaseda *et al.* 2013). Moreover, this climatic hiatus has been recently explained by an increase of the ocean heat content at depth (Drijfhout *et al.*, 2014). The random climate variability from one year to another is not surprising given the high nonlinearity and complexity of the Earth climate system. Temporary stagnations of global warming can be essentially related to ocean dynamics.

Ocean temperature rises induce side effects that could be of consequence, if not catastrophic, but that are yet still poorly understood. Amongst these effects, there is its contribution to the rise of average sea level, currently estimated to be over 1mm/year. (*e.g.*, Cazenave *et al.*, 2014).

The oceans and seas produce another direct effect on climate change: it is likely that rising temperatures are progressively leading to an intensification of the global water cycle (Held and Soden, 2006; Allan *et al.*, 2010; Smith *et al.*, 2010; Cubash *et al.*, 2013; Rhein *et al.*, 2013).

Water vapor being a greenhouse gas, it has a role in accelerating global warming, and consequently water evaporation. Changes in the water cycle can be observed using the variations in salinity as a proxy. An assemblage of recent data shows that surface salinity has changed over the past five decades, with an increasing contrast between the North Atlantic and the North Pacific basins (Durack and Wijffels, 2010; Hosoda *et al.*, 2009; Rhein *et al.*, 2013).

Salinity measurements at different depths also reveal changes (Durack and Wijffels, 2010; Rhine *et* *al.*, 2013). The most noteworthy observation has been a systematic increase of the constrast in the salinity between the subtropical gyres, that are saltier, and high latitude regions, particularly the Southern Ocean. At a global scale, these contrasts point to a net transfer of fresh water from the tropics towards the poles, thus implying an intensification of the water cycle. In the North Atlantic, a quantitative assessment of the thermal energy storage and freshwater flux over the past 50 years confirms that global warming is increasing the water content of the atmosphere, thus leading to the intensification of the water cycle (Durack *et al.* 2012).

The sea temperature rise also modifies its dynamics as well as the transfers of heat and salt, thus locally disrupting the surface exchanges of energy with the atmosphere. Thermohaline circulation can also be disturbed and may affect the climate at a global scale by significantly reducing heat transfer towards the Polar Regions and to the deep ocean. According to the IPCC (Intergovernmental Panel on Climate Change), it is very likely that the thermohaline circulation will slow down during the 21st century, although it should be insufficient to induce a cooling of the North Atlantic region. Increasing ocean temperature also has a direct impact on the melting of the base of the platforms of the continental glaciers surrounding Greenland and Antarctica, the two major continental water reservoirs (Jackson *et al.*, 2014; Schmidko *et al.*, 2014; Rignot *et al.*, 2014). Hence, although it was known that global warming is enhancing glacial melt, it is now proven that the heating of the oceans is contributing primarily to the melting of ice shelves that extend the Antarctic ice cap over the ocean. For example, considering that Antarctica holds about 60% of the world's fresh water reserves, recent studies show that the melt of the base of the Antarctic ice caps has accounted for 55% of the total loss of their mass between 2003 and 2008, representing a significantly large volume of water (Rignot *et al.*, 2014).

Ocean warming affects the biogeochemical mass-balance of the ocean and its biosphere[1]. Although most of these aspects have been documented, it is noteworthy to mention that the warming of the oceans can also impact the extent of their oxygenation: the solubility of oxygen decreases with increasing water temperature: the warmer the water, the lower the dissolved oxygen content. The direct consequences involves losses of marine life anad its biodiversityand restrictions in the habitats (*e.g.* Keeling *et al.* 2010).

Compared to the atmosphere, the ocean presents two characteristics that confer it an essential role in the climate system:

1. Its thermal capacity is more than 1000 fold that of the atmosphere and allows the ocean to store most of the solar radiation flux and surplus energy generated by human activities.
2. Its dynamics are much slower than in the atmosphere, with a very strong thermal inertia; at time scales that are compatible with climate variability, the ocean therefore keeps a long-term memory of the disturbances (or anomalies) that have affected it.

However, the world ocean is still poorly known due to its great size and to the inherent technical difficulties encountered in oceanographic observation (*e.g.* the difficulty of high precision measurements at pressures exceeding 500 atmospheres; the need to collect *in situ* measurements everywhere in the ocean aboard research vessels that are operated at great costs). In addition, ocean dynamics can be very turbulent and subsequent interactions with the atmosphere, extremely complex. To unveil these unknowns and uncertainties will be an essential step to predict the future evolution of the climate in a more reliable manner. Observations and measurements are irreplaceable sources of knowledge. It is therefore necessary to improve the nature and quantity of ocean observations with the aim to establish a long-lasting, internationally coordinated, large-scale ocean-observation system.

1 In particular refer to « The ocean carbon pump » and « the ocean acidification and de-oxygenation » scientific sheets

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The Ocean: a Carbon Pump

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The ocean contains 50 times more carbon than the atmosphere and is exchanging large amounts of CO_2 with the atmosphere every year. In the past decades, the ocean has slowed down the rate of climate change by absorbing about 30% of human emissions. Whereas this absorption of anthropogenic CO_2 is today the result of physical-chemical processes, marine biology is playing an important role in the ocean carbon cycle by sequestering carbon in the deep ocean. Changes in any of these physical, chemical and biological processes may result in climate feedbacks that either increase or decrease the rate of climate change, although knowledge of such interconnections is today still limited. The feedbacks between climate, the ocean, and its ecosystems need to be better understood in order to predict the co-evolution of atmospheric CO_2 and climate change more reliably and also to understand the characteristics of a future ocean.

A MAJOR ROLE FOR THE OCEAN IN THE EVOLUTION OF ATMOSPHERIC CO_2

The cycling of carbon involves a wide range of physico-chemical and biological processes contributing to a series of interconnected carbon reservoirs in the Earth System. A schematic diagram of the global carbon cycle showing the relative importance of each of these processes is shown in Figure 1. The global cycle was roughly balanced before the industrial era. During the past 200 years, atmospheric CO_2 has increased from less than 0.03% to more than 0.04%, as a result of fossil fuel burning, cement production, deforestation and other changes in land use. It is considered that such a rapid change is at least ten times faster than any other that has happened during the past 65 million years (Portner *et al.*, 2014; Rhein *et al.*, 2014).

Since the beginning of the industrial era, the ocean has played a key role in the evolution of atmospheric CO_2 by absorbing a significant fraction of CO_2 emitted into the atmosphere by human activities, deforestation and burning of fossil fuels. During the past decade (2004-2013), the global ocean has absorbed 2.6 billion tonnes of carbon per year, representing nearly 30% of anthropogenic emissions over this period. Since 1870, the amount of carbon absorbed by the ocean has reached 150 billion tonnes – also representing 30% of anthropogenic emissions over this period. By absorbing this greenhouse gas, the ocean thus contributes to slow down human-induced climate change.

A NATURAL OCEAN CARBON CYCLE INVOLVING PHYSICO-CHEMICAL AND BIOLOGICAL PROCESSES

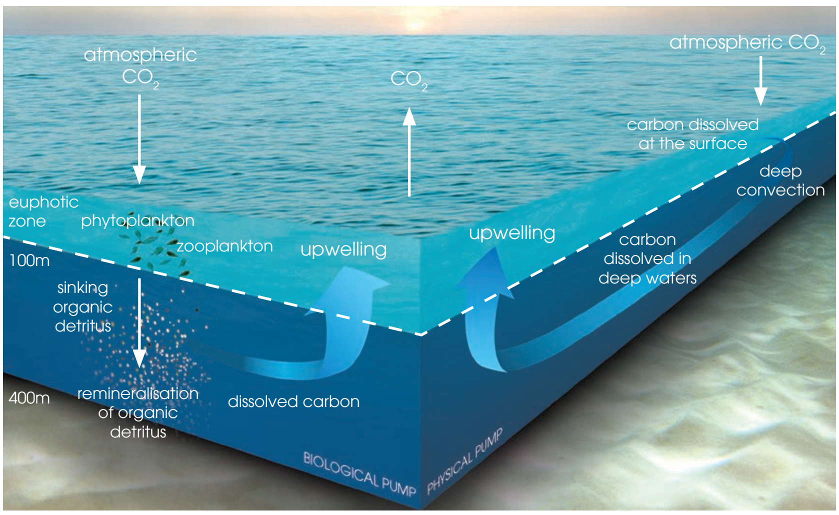
Anthropogenic carbon absorbed by the ocean feeds a considerable natural carbon reservoir. The ocean contains about 40,000 billion tonnes of carbon (40,000PgC), mainly in the form of inorganic carbon dissolved in seawater. This amount represents 50 times the size of the atmospheric reservoir. Each year, the ocean naturally exchanges with the atmosphere almost a hundred billion tonnes of carbon as CO_2.

In the ocean, this carbon, which prevails essentially in the form of bicarbonate ions (HCO_3^-), is not evenly distributed, as dissolved carbon concentrations are higher at depth than at the surface. The spatial distribution of carbon with depth controls atmospheric CO_2 levels, as only the inorganic carbon from the sea surface is in contact with the atmosphere and contributes to the exchange of CO_2 between the atmosphere and the ocean. This vertical gradient of carbon can be explained by both physico-chemical and biological processes.

- **Biological Processes**

Phytoplankton living in the sunlit layer of the ocean use light energy to perform photosynthesis. They take up nutrients as well as dissolved inorganic carbon to produce organic matter. The production of these carbon-based materials supported by solar energy is called primary production. It represents the base of the trophic chains from which other non- photosynthetic organisms can feed on. Photosynthetic activity is therefore an efficient mechanism for extracting CO_2 from the atmosphere and transferring the carbon into living organisms. Surprisingly, the organisms that contribute to primary production represent only a small organic carbon pool (~3PgC), but they are capable of generating large amounts of dissolved organic carbon (DOC: ~700PgC) to sustain the food chains because their turnover is very rapid, from a few days to several weeks.

A fraction of produced organic material exits the surface layer as sinking particles, thus transferring the surface carbon towards the deep layers of the ocean (Figure). Before being sequestered to the deep the atmospheric carbon fixed by photosynthetic organisms undergoes a series of transformations: phytoplankton can be directly consumed by zooplankton, or indirectly by heterotrophic bacteria, which will in turn be eaten by larger organisms. During this process, a fraction of the total carbon biomass (average value of 10%) ends up as detrital matter, fecal pellets or dead cells which compose the stock of marine particles. In turn, a fraction of these particles (in suspension or sinking) also undergoes a series of transformations before reaching the base of the mesopelagic layer (typically 1000m depth), thus sequestering atmospheric CO_2 for thousands of years. It is generally believed that 0.1 to 1% of the carbon-containing material at the surface finally reaches the base of the mesopelagic zone, then the sediment where it can turn into fossil fuel deposits. The remaining organic matter is remineralized through respiration, and CO_2 returns to the atmosphere. Each year, nearly 10 billion tonnes of carbon are exported from the surface layer and are responsible for most of the carbon vertical gradient. All of these



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

processes that contribute to the governing role of marine biology on the carbon cycle in the ocean are part of the so called biological carbon pump (Figure).

Although only a small fraction (~ 0.2PgCyr^{-1}) of the carbon exported by biological processes from the surface reaches the sea floor, the fact that it can be stored in sediments for millennia and longer (Denman *et al.*, 2007; Ciais and al., 2014) means that this biological pump is the most important biological mechanism in the Earth System allowing CO_2 to be removed from the carbon cycle for very long periods of time.

Over geological time-scales, the biological carbon pump has formed oil deposits that today fuel our economy. In addition, biochemical sedimentary rocks such as limestone are derived principally from calcifying corals, molluscs, and foraminifera, while the considerable reserves of deep sea methane hydrates (or clathrates) are similarly the result of hundreds of millions of years of activity of methanogenic microbial consortia. Considering that, each day, large amounts of CO_2 that have been trapped for millions of years are discharged into the atmosphere (the order of magnitude is now probably about a million years of trapped carbon burned by humankind each year), it is easier to understand the rapidity at which present climate change is taking place. Consequently, there is a dramatic difference between the rate of CO_2 sequestration by photosynthesis and rate of CO_2 discharge into the atmosphere. The anthropogenic emissions will therefore need to be redistributed by the global carbon cycle until a new steady state is reached.

- **Physico-Chemical Processes**

A second series of processes, comprising physico-chemical activities, also contributes to the increasing carbon distribution with depth. The cooling of surface waters at high latitudes favours their ability to dissolve atmospheric CO_2 (mainly by increasing the solubility of the gas) as well as increasing their density. These heavy surface waters plunge down to great depths, in this way exporting the CO_2 and preventing it from further contact with the atmosphere. This process that contributes to the vertical gradient of ocean carbon is known as the physical pump or solubility pump (Figure).

Despite the fact that biological processes are responsible for the majority of the vertical gradient of natural carbon in the ocean, the physico-chemical processes can nevertheless explain the anthropogenic carbon sink observed today. Indeed, excess CO_2 in the atmosphere will lead to a net carbon flux to the ocean due to the disproportion induced between atmospheric and oceanic CO_2 concentrations. Subsequently, once the anthropogenic CO_2 enters surface waters, it is transported by ocean currents and progressively mixed with the sub-surface waters.

IS THE OCEANIC CARBON SINK GOING TO SATURATE?

To date, and since the beginning of the industrial era, the ocean has continuously absorbed a relatively constant part of the amount of CO_2 emitted by human activities. However, many studies based on theoretical considerations, in situ observations, controlled laboratory experiments, or supported by models, suggest that several processes may lessen or slow-down this natural carbon sink.

The first series of processes is related to the chemistry of carbonates (exchanges between CO_2, HCO^{3-} and CO_3^{2-}) and can eventually lead to a saturation of the oceanic carbon sink. Indeed, the dissolution of anthropogenic carbon dioxide decreases the ocean carbonate ion content and therefore the buffer effect of the ocean, which in turn increases the proportion of CO_2 in comparison to the other forms of dissolved inorganic carbon species and thus may reduce the efficiency of the natural carbon sink. This phenomenon occurs in parallel with the process of ocean acidification, and could potentially have serious impacts on life in the ocean.

The second series of processes is related to the feedback between climate and the carbon cycle. This concerns the feedback between anthropogenic climate change and different carbon absorption phenomena. As mentioned earlier, climate change leads to modifications in water temperature, ocean currents, and production of organic matter in the ocean. If these changes should boost the carbon sink, they would curb climate change and induce a negative feedback. On the contrary, in the event of a weakening of the carbon sink, the changes would lead to a positive feedback that would in turn accelerate the phenomenon.

Once more, different processes are involved. For example, the increase in the temperature of the ocean weakens the ocean carbon sink. An increase by 2 or 3°C in sea surface temperature decreases the solubility of CO_2 by a few percent, and thus the capacity of the ocean to absorb carbon dioxide. Another effect could accentuate this saturation of the carbon sink: in response to rising temperatures, climate models predict an increase in vertical stratification of the ocean. In other words, vertical mixing, which tends to homogenize the surface waters with the deep, would diminish and the resulting stratification would reduce the present penetration of anthropogenic CO_2 towards the ocean depths.

The future of the biological pump is difficult to predict. Even a qualitative estimate of the effect of changes in marine ecosystems on the ocean carbon sink remains highly speculative. More specifically, because the activity of the biological pump is likely to be strongly regulated by net primary production (NPP), it is important to consider the effects of climate change on photosynthetic activity. On land, as the CO_2 supply is generally limiting for photosynthesis, the increase in anthropogenic CO_2 tends to stimulate plant growth (known as the carbon dioxide fertilization effect). This does not appear to be the case in marine systems because Dissolved Inorganic Carbon (DIC) is not limiting for carbon fixation by photosynthesis. However, photosynthesis is also strongly affected by temperature, and the upper ocean has significantly warmed during the last 150 years. In addition to temperature, light, inorganic nutrients, and the density-dependent stability of the surface mixed layer (González-Taboada and Anadón, 2012; Portner *et al.*, 2014) are all likely to affect photosynthetic activity, as are oxygen, pH, and salinity. Environmental variability and the displacement of organisms by ocean currents cause variability in phytoplankton productivity, competitiveness, and natural selection, which are also likely to result in changes in carbon sequestration. It is therefore crucial to estimate how the production of organic material by phytoplankton is going to be affected by changes in environmental conditions of surface water: for example rising water temperature, melting of sea ice and changes in dissolved nutrient availability (nitrates, phosphates).

Modelling approaches predict an overall reduction in global mean NPP as a result of climate change, albeit with significant latitudinal variations. One of the factors leading to this reduction is the predicted expansion of oligotrophic gyres as nutrient availability decreases with the intensification of stratification. Predictions indicate increasing NPP at high latitudes (because the amount of available sunlight should increase as the amount of water covered by ice decreases). However this would be counterbalanced by a decrease of NPP in temperate and tropical latitudes (because of reduced nutrient supply). The types of plankton species that would dominate the ecosystem in altered conditions should also be estimated, as the composition of plankton can significantly affect the intensity of CO_2 absorption. The role of certain phytoplankton populations, such as diatoms, can be particularly significant. They are characterised by relatively large cell sizes (tens to hundreds of micrometers), which allows them to sink rapidly. They are therefore responsible for the export of a large fraction of carbon to the deep ocean. Nonetheless, diatoms cannot thrive in nutrient depleted conditions. In this case they could be replaced by other types of smaller (<10 microns) phytoplankton cells that are better adapted to poor nutrient conditions. Although such cells are abundant in the ocean, due to their small size they are principally recycled within the surface layer, and thus have a very minor role in carbon export to the deep. A decrease in the diatom/

small cell community ratio could thus greatly disrupt the intensity of the biological pump, especially in the polar regions.

Despite these multiple levels of uncertainty - the most important being the biological response to climate change - the different predictions produced by numerical models that couple the climate system and the carbon cycle all point to a declining ocean carbon sink due to global warming. Even though this ocean sink is unlikely to become a source there is no doubt that a decrease will affect the evolution of the CO_2 in the atmosphere and, ultimately, climate change itself. By 2100, the feedback between the climate and the carbon cycle (including the response of the terrestrial biosphere to climate change) could even be responsible for an additional increase in atmospheric CO_2 of several tens of ppm!

The future evolution of the oceanic carbon sink, as predicted by models coupling the climate and carbon cycle at a global scale, still remains very uncertain. The last IPCC report points to a number of poorly constrained processes that explain the wide range of uncertainties associated with the predictions: these primarily include biotic responses to climate change and the changes in the biological pump (the complexity of biological processes being extremely difficult to include in climate models). Other processes related to the representation of small-scale features (eddies) and to the consideration of particularly complex coastal areas are also mentioned in this report.

A ROLE IN OTHER BIOGEOCHEMICAL CYCLES

Besides its role in both the carbon cycle and the evolution of atmospheric CO_2, it must be emphasized that the ocean also plays a key role in other major biogeochemical cycles, including nitrogen, phosphorus and sulphur that are liable to affect the biogeochemical balance of our planet.

In the mid-1980s, several scientists including James Lovelock suggested that ocean ecosystems, especially phytoplankton, are able to regulate the world climate by releasing the sulphurous gas dimethyl sulphide or DMS. Once in the atmosphere, this gas favours the formation of tiny sulphate particles which play a role as condensation nuclei for clouds, thus contributing to an increase in cloud cover. This hypothesis, which is still called the CLAW hypothesis (based on the first letter of the surname of each of the authors; Charlson *et al.*, 1987), states that the ocean ecosystem reacts to an increase in temperature by increasing productivity. This in turn leads to increased emissions of DMS, resulting in a temperature drop due to the enhanced cloud cover. This would be a self-regulating negative feedback loop. It is an example of regulation that allowed Lovelock to build the Gaia theory, stipulating that several self-regulatory processes, including the sulphur cycle, allow the planet Earth to be considered as a living organism.

More than 20 years later, research projects have revealed the complexity of the sulphur cycle in the ocean, but have neither confirmed nor refuted this hypothesis. It is not yet known how, why and what species of phytoplankton can release the precursory sulphur compounds for the formation of DMS. Knowledge is therefore still lacking to determine whether anthropogenic climate change will result in a decrease or an increase in DMS emissions from the ocean.

MANIPULATION OF THE CARBON PUMP TO OFFSET CO_2-INDUCED CLIMATE CHANGE

Humankind has disrupted the steady state balance of the global carbon cycle and has brutally contributed to the modification of the composition of Earth's atmosphere, just as bacteria, protists and the biosphere in general have played a role in the shaping of the Earth's atmosphere in the past. As other events have marked the history of our planet in the past, these present changes provoked by human activities will significantly affect the Earth System. Our duty as inhabitants of the planet Earth is now to formulate predictions and to react in the best possible way to avoid disaster.

Studies have suggested that an artificial enhancement of the ocean carbon pump might improve carbon sequestration in the ocean, thus counterbalancing CO_2-induced climate change. For example, primary productivity of phytoplankton could be stimulated by adding nutrients such as iron to surface waters where they are limiting. There is currently no consensus on the efficiency of such methods, which are limited to a few field experiments. Moreover, alternative geoengineering approaches focusing on solar radiation management are not capable of resolving the issue of ocean acidification.

To conclude, it remains essential to protect the ocean carbon pump that contributes to more than half of the CO_2 sequestered each day. This can only be done by preserving the oceans, their marine life and their planktonic ecosystems. The carbon balance of the different parts of the carbon cycle also needs to be better characterised by carrying out further fundamental research in this field.

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Sea Level Rise

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Measurements from tide gauges and satellites have shown that the sea is rising globally at an average rate of about 1.7mm per year since the beginning of the 20th century, a direct consequence of human-driven global warming, although there is strong regional variability. This increase is mainly due to two factors: the increase in ocean temperature resulting in expansion of sea water, and the melting of continental ice sheets, glaciers and ice caps with an input of fresh water into the ocean. Despite uncertainties, proposed scenarios indicate that sea levels will continue to rise at a faster pace than during the 20th century, reaching an increase of more than 25cm (best case) and 82cm (worst case but likely underestimated) by 2100.

MAREGRAPHIC MEASUREMENTS DURING THE 20TH CENTURY

Direct observation of changes in sea level began with the industrial era and the systematic installation of tide gauges in a few harbours across northern Europe, then progressively in other areas of the world. These instruments, originally developed to measure the tides, provide us with precious data on the evolution of sea level during the twentieth century. Although few in numbers and poorly distributed over the globe, the historical tidal series indicates that since the beginning of the twentieth century, the sea has globally been rising at an average speed of about 1.7mm per year (Figure1, left).

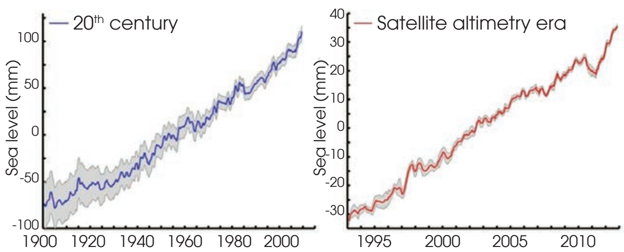

Fig.1— Evolution of the global average sea level, estimated from the reconstruction by Church and White (2011) over the twentieth century (left) and from satellite altimetry over the 1993-2012 period (source: AVISO). The uncertainty associated with each of the curves is in grey. The annual and semi annual cycles have been removed. Note the vertical scale difference between the two curves. From Cazenave & The Cozannet (2014).

THE OBSERVATION OF CHANGES IN SEA LEVEL FROM SPACE

Since the early 1990s, routine measurements of the rising sea levels have been made from space, thanks to high-precision altimetry satellites like Topex/Poseidon, Jason-1/2, ERS-1/2, Envisat and recently Saral/Alika and Cryosat (Ablain *et al.*, 2014). Satellite observations have a major advantage in comparison with the tide gauge: they provide a quasi-global observation of the entire ocean, with a revisit time of a few days. Figure 1 (right) illustrates the evolution of the sea level measured by altimetry satellites between 1993 and 2013. During this period, the rise in sea level was almost linear at a speed of 3.2±0.4mm/year (Cazenave *et al.*, 2014). This increase is the double of that recorded by tide gauges during the twentieth century, suggesting an acceleration of sea level rise since the early 1990s. Thanks to its complete coverage of the global ocean, satellite altimetry also revealed that the rise in sea level is not uniform. It presents a strong regional variability (see Fig.2) from regions such as Western Tropical Pacific where the sea level is rising 3 times faster than the global average, to other regions such as the western United States coastline, where the sea level is dropping at a rate of 1 to 2mm/year.

THE CAUSES OF THE CURRENT RISE IN THE GLOBAL MEAN SEA LEVEL

On a global average, the current rise in sea level is a direct consequence of anthropogenic global warming (Church *et al.*, 2013). It has two main causes:

1. Increasing ocean temperatures and associated thermal expansion (when the temperature increases, the sea water expands and sea level rises)
2. The melting of continental ice, glaciers and ice caps (freshwater flows to the sea due to melting continental ice lead to rising sea level). In addition to these processes, a small contribution also results from liquid water exchanges with the land (0.38mm/year over the 1993-2010 period).

- **Thermal expansion**

Thanks to sea temperature measurements collected from sensors dropped overboard from the stern of merchant ships during the past five decades and from the automatic floats from the international Argo project during the past ten years, oceanographers have observed that the ocean is getting warmer. Sea water expands with increasing temperature, thus leading to a rise in sea level. It is estimated that during the altimeter period (*i.e.* since 1993 and the beginning of satellite observations), this contribution can explain for 30% of the rise in global sea level (1.1±0.3mm/year between 1993 and 2010; Church *et al.*, 2013).

- **Melting glaciers**

Glaciers represent the whole of the continental ice masses, except for the two vast Greenland and Antarctic ice caps. There are more than 200,000 glaciers, covering about 730,000 km² of emerged lands. Since the end of the Little Ice Age around 1850, observations (from in situ measurements of glacier mass balance, altimetry and recently space gravimetry) have evidenced glacier retreat in almost all mountain ranges. This is partly explained by their delayed response to natural global warming following the Little Ice Age. However, the acceleration of glacier mass loss observed since the mid-1980s has been attributed to the recent anthropogenic warming (Marzeion *et al.*, 2014). During the altimeter period between 1993 and 2010, the glaciers are estimated to have contributed to a 0.9mm/year sea level rise (Church *et al.*, 2013).

- **Mass loss of the polar ice caps**

The mass loss of the polar ice caps can be observed and estimated primarily with three techniques: Radar or laser altimetry (which measure changes in the elevation of ice sheets since 1991), Spatial gravimetry (which provides direct mass changes of the ice cap with time) and the flux method (calculation of the difference between climate model estimates of surface snow accumulation and the flow of ice reaching the ocean at the grounding line of the ice caps) (Rignot *et al.*, 2014). An assessment of these observations over the past 20 years (Shepherd *et al.*, 2012) indicates a very strong mass loss in the coastal regions of Greenland and West Antarctica. Together, these losses represent an increase in sea level of 0.6mm/year over the 1993-2010 period (Church *et al.*, 2013).

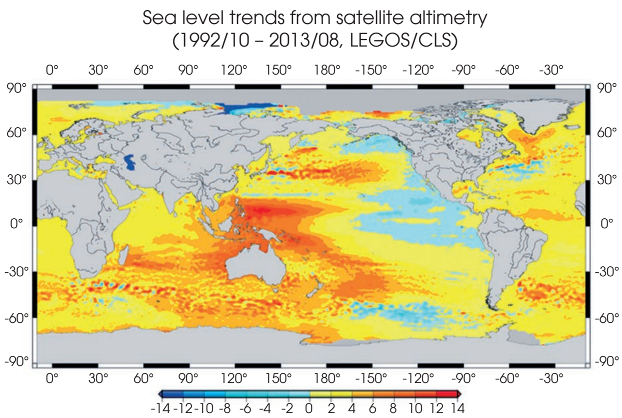

Fig.2— Global map of the geographical distribution of rates of sea level change (1993-2013) according to altimeter measurements from Topex/Poseidon, Jason-1/2, ERS-1/2 and Envisat (source: LEGOS).

REASONS FOR THE REGIONAL VARIABILITY OF SEA LEVEL

At a regional scale, the heat accumulation in the ocean and its associated thermal expansion generate most of the variability in sea level. The heat in the ocean is redistributed irregularly by ocean circulation (Stammer *et al.*, 2013) in response to atmospheric forcing (in angular momentum, heat and freshwater). Depending on the region, different processes are at work. For example in the western tropical Pacific, the intensification of trade winds observed for twenty years have caused a deepening of the thermocline in the western part of the basin, inducing the formation of a thicker layer of warm surface water and therefore a marked rise in sea level (Timmermann *et al.* 2010; Stammer *et al.*, 2013.).

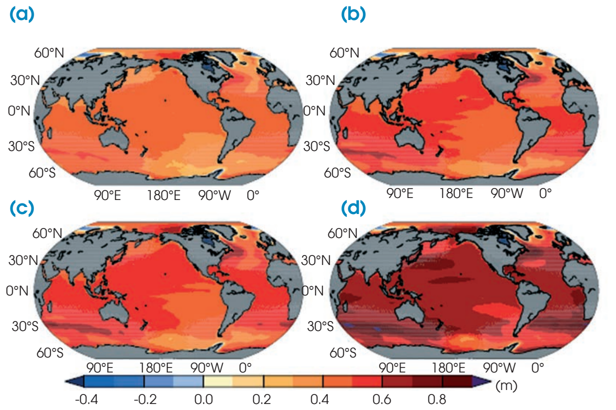

Fig.3— Overall average (21 CMIP5 models) of the change in relative sea level for RCP2.6 scenarios (a), 4.5 (b), 6.0 (c) and 8.5 (d). The impact of thermal expansion of the oceans, the mass of continental ice, continental stocks of liquid water and post-glacial rebound have been taken into account (adapted from Church *et al.*, 2013).

SEA LEVEL RISE IN THE FUTURE

In response to past and future emissions of greenhouse gases, global warming will continue in the future. Consequently, the increase in sea level will also continue, largely due to the melting of land ice and thermal expansion of the oceans. The challenge is to estimate the magnitude of this increase, with the regional disparities, and associated uncertainties. The uncertainties derive from two major sources: firstly, the lack of understanding of certain climatic processes that affect changes in sea level (*e.g.* this is the case for the ice flowing from the polar ice caps to the ocean) and secondly, the uncertainty concerning future gas emission scenarios for the anthropogenic greenhouse effect. Indeed, different scenarios involving emissions of greenhouse gases (expressed in terms of radiative forcing: RCP2.6, RCP4.5, RCP6.0 and RCP8.5, IPCC 2013) and the response of the climate system (expressed as the increase in the global temperature of the Earth) can occur for the coming decades (IPCC 2013). Each scenario indicates a rise in sea level between 1986 and 2000 and between 2080 and 2100, as they all forecast an increase in sea temperature and the melting of land ice. The extent of the sea level rise would vary between 25cm (best case scenarios RCP2.6) and 82cm (worst-case scenarios RCP8.5). In all cases, a simulation of the rise of the level of the sea between now and 2100 indicates that it will be faster than during the twentieth century. By 2100, the rate of sea level rise would reach 8-16mm/year for the RCP 8.5, which is similar to that during the last deglaciation. Moreover, in the same way that present changes in the current sea level are not uniform, it is expected that changes in sea level at the end of the XXI[st] century will display significant regional differences (Figure 3, Yin *et al.*, 2010). For example, considering the RCP8.5 scenario, the sea level could drop slightly in certain areas of the Arctic, while it could increase by more than 70cm along the east coast of the United States. It is therefore essential to take these differences into account and to model them correctly in order to anticipate future rises in sea level in coastal areas. At the moment, this is a very active research topic.

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Ocean Acidification

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Each day, the oceans absorbs about a quarter of the CO_2 produced by human activities, causing a chemical modification of seawater that results in ocean acidification. The dissolution of CO_2 in seawater causes an increase in acidity (decrease in pH) and a decrease in the availability of carbonate ions (CO_3^{2-}) which are one of the building blocks required by marine plants and animals to make their skeletonnes, shells and other calcareous structures. Ocean acidity has increased by 30% in 250 years, and could triple by 2100. It threatens species such as oysters and mussels, and will also have an impact on marine food chains. Our understanding of the effects of ocean acidification on marine life are still only rudimentary.

OCEAN ACIDIFICATION

Every day our oceans absorb about 1/4 of all man-made carbon dioxide (CO_2). The result? Ocean acidification, with consequences for some marine plants, animals and ecosystems.

WHAT IS OCEAN ACIDIFICATION?

Most of us have already heard about climate change and global warming, caused by the greenhouse gas effect. We also know that human activities are the culprit; in particular the carbon dioxide emissions (CO_2) produced by industry and cars. But *ocean acidification* remains poorly known. This is not very surprising, as the consequences of this phenomenon were only recently discovered. Yet, the cause is once again carbon dioxide. In fact, ocean acidification is sometimes called "the other CO_2 problem".

THE CHEMISTRY

All of the CO_2 that we produce every day does not remain in the atmosphere. Instead, around one fourth is absorbed by our oceans. Without the oceans, the proportion of atmospheric CO_2 would be higher, leading to more severe global warming. We are therefore very lucky to have our seas and oceans! For a long time researchers thought that this absorption of CO_2 would remain without major consequences for the oceans and the organisms that live there. But they realized, around 15 years ago, that the dissolution of CO_2 in seawater had been changing its chemistry: leading to a reduction in pH (the measure of the acidity of a liquid) and in the concentration of carbonate ions (CO_3^{2-}), an important building block for the creation of shells, skeletonnes and other calcareous structures in marine plants and animals.

ACIDITY AND THE PH SCALE

You must be familiar with some acidic food such as lemon or vinegar. Well, CO_2 is an acid gas. You can see it in sodas: the small bubbles are, in fact, CO_2 bubbles. After being absorbed by the oceans, the CO_2 dissolves in seawater, leading to an acidification. This does not mean that oceans are becoming acid, only that their chemistry is progressively changing towards a higher level of acidity. The acidity of a liquid is determined by its concentration of hydrogen ions H^+ (protonnes). It is not practical to refer to the concentration of protonnes, as numbers are very small. To simplify, we use the pH scale with values ranging from 0 to 14. The lower the pH value, the higher the acidity of the liquid. A liquid with a pH of 7 is called *neutral*, one with a pH lower than 7 is acid, and if the pH is higher than 7 it is said to be *basic*. The pH scale is a bit unusual, much as the Richter scale used to measure the magnitude of earthquakes a liquid with a pH of 6 is 10 times more acidic than a liquid with a pH equal to 7, 100 times more acidic that a liquid with a pH of 8 and 1000 times more acidic than a liquid with a pH of 9.

THE NAME

Why is this phenomenon called "ocean acidification", even if our oceans will never actually become acidic (pH < 7)? Acidification is a process: the decrease in pH (increase in hydrogen ions and acidity). The word "acidification" refers to lowering pH from any starting point to any end point on the pH scale. This terminology can be compared to the one used for temperature: if the temperature of the air goes from -20 to -10, it is still cold, but we call it "warming".

A LITTLE BIT OF HISTORY

Ocean acidity has increased by 30% in 250 years, or since the beginning of the industrial revolution (a drop in pH from 8.2 to 8.1). Model projections have shown that at the present rate of CO_2 emissions the acidity of ocean surface water could triple by the end of this century. The current speed of CO_2 absorption is 100 times higher than has occurred naturally over the last 300 million years.

IMPACTS ON MARINE ORGANISMS

The absorption of CO_2 by seawater does not only increase the number of protonnes (hydrogen ions, H^+) but it also lowers the number of certain molecules - the carbonate ions (CO_3^{2-}) - used by numerous marine organisms to build their skeletonnes and shells (corals, mussels, oysters etc.). Many of these calcifying plants and animals will thus face difficulties when building these structures, and their skeletonnes and shells might even dissolve. When seawater acidity reaches a certain threshold it becomes corrosive to limestone, the material used to form shells and skeletonnes.

Researchers have performed laboratory studies on the process of building these calcareous structures, in organisms exposed to conditions of ocean acidification projected to occur in the future. Negative effects have been observed in some species, for instance in pteropods and calcifying algae (see pictures 1 and 2). Other organisms might benefit from ocean acidification. For example, for some plants more CO_2 means increased photosynthesis.

WHAT COULD BE THE IMPACT OF OCEAN ACIDIFICATION ON HUMANS?

Ocean acidification could have a direct impact on organisms that we consume and that form calcareous shells, such as clams and oysters. Negative effects on zooplankton, similar to those observed in pteropods, could have indirect consequences for humans. Everything is connected in the ocean. Many organisms depend on plankton or corals, for instance, as their source of food and habitat. Ocean acidification could therefore impact food chains and biodiversity in certain ecosystems. For example, in the North Pacific and Arctic oceans the tiny pteropod is eaten by salmon. Salmon is an essential food resource and salmon fisheries employ many people.

WHAT CAN WE DO TO REDUCE OCEAN ACIDIFICATION?

Seawater chemistry will remain altered for centuries to come even if we stop all CO_2 emissions right now. But it is still possible to slow down ocean acidification and reduce its impacts. More or less realistic geo-engineering techniques have been proposed to limit ocean acidification (for instance, discharging basic compounds into the oceans to counter acidification and increase the pH). However, the only proven, effective and risk-free solution is to attack the root of the problem, namely the rise in CO_2 emissions. Emissions can be reduced at several levels, in particular through political negotiations on the replacement of fossil fuels with renewable sources of energy, carried out at national and international level. But each of us can bring a contribution. We can reduce our emissions by taking the train instead of the car, for instance, or by limiting our use of electricity, and we can talk about this problem with friends and family so that they learn how to reduce their emissions too.

FOR MORE INFORMATION

- Laboratoire virtuel – http://i2i.stanford.edu/AcidOcean/AcidOcean_Fr.htm
- Animation sur l'acidification en français – www.youtube.com/watch?v=KqtxGZKItS8
- Animation projet BNP Paribas eFOCE – www.youtube.com/watch?v=QhgQ4unMVUM
- Animation « Hermie the hermit crab » – www.youtube.com/watch?v=RnqJMlnH5yM Great Barrier Reef Marine Park Authority
- Brochures en français – www.iaea.org/ocean-acidification/page.php?page=2198
- Résumé à l'attention des décideurs – www.igbp.net/publications/summariesforpolicymakers/summariesforpolicymakers/oceanacidificationsummaryforpolicymakers2013.5.30566fc6142425d6c9111f4.html

The Deep Ocean: Which Climate Issues?

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The deep ocean (200m below the surface to 11,000m) represents over 98% of marine waters in volume. The image of a stable and homogeneous environment over vast areas, with low biological activity, does not actually reflects the diversity of deep-sea ecosystems nor their sensitivity to climate change. Even on the abyssal plains, variations in abundance of key species have been attributed to changes in the photosynthetic productivity at the surface of the ocean. Moreover, many biodiversity and productivity 'hot-spots' of the deep seafloor, and their foundation species such as deep-sea corals could be particularly vulnerable to the already observable changes at great depths, such as local or regional warming deep water, acidification and deoxygenation and modifications of the circulation of water masses. This vulnerability questions our ability to anticipate the consequences of climate change on poorly known ecosystems and the services they provide.

DYNAMIC DEEP-SEA ECOSYSTEMS IN A HETEROGENEOUS ENVIRONMENT

When it comes to climate, the deep ocean is first seen as a vast saltwater reservoir that allows heat distribution around the globe via thermohaline circulation. The sequestration of atmospheric CO_2 released by human activities, and of the excess heat that it generates, operates on secular to millenar scales during which ocean waters, after plunging to depths, flow over the seafloor across ocean basins before reemerging at the surface.

We can consider that the upper limit of the deep ocean lies about 200m below the surface, where there is no sunlight or seasonal temperature variations, and extends to the ocean floor down to a maximum depth of 11,000m. This environment represents over 98% of marine waters in volume. It is described as stable and uniform over large areas, isolated from continents and the atmosphere, with water chemical properties (like pH and oxygen, nitrate, CO_2 contents) changing very slowly as organic matter transported from the surface is being degraded by microorganisms.

This large scale view of the ocean circulation is mirrored in the perception of a deep ocean where biological activity is sparse, populated by species with slow metabolisms adapted to a cold and dark environment, low nutritional resources, and high pressures. Considered as uniform and quasi-desertic, these oceanic regions would be barely affected by ongoing climate change, or only in the very long term. However, this view is inconsistent with our current knowledge of the wide variety of deep-sea ecosystems. An increasing number of studies show that most of these deep-sea ecosystems interact with the climate system. Even the abyssal plains that are sustained by limited food supply, formed by planktonic remains and other organic debris, are subject to seasonal variations. In particular, changes in species abundance have been observed, revealing an unexpected ecological dynamics attributed to differences in surface ocean photosynthetic productivity from year to year.

Moreover, beside the vast abyssal sedimentary domain occupying 75% of the ocean floor, we can no longer overlook other types of deep-sea environments that are, at least, of equal ecological or societal importance. The topography of the ocean floor is indeed similar to the reliefs of continents (*i.e.* expanding over a depth range of 11,000m in the deepest trench, to be compared to the 8,500m of Mt. Everest). Interplaying with oceanic currents, this rugged seabed is home to a mosaic of ecosystems themselves composed of fragmented habitats (Ramires-Llodra *et al.* 2010). Today's satellite imaging techniques enable a detailed view of their distribution and diversity at global scale. This diverse environment creates major biomes equivalent to those linked to terrestrial climates (tundra, savanna, etc.) to which species have adapted. Like terrestrial or coastal environments, the deep ocean also hosts 'hot-spots' of biodiversity and productivity, which functioning and associated "services" could be particularly vulnerable to climate change impacts and ocean acidification.

For example, seamounts that rise from hundreds to thousands of meters above the abyssal plains can promote vertical exchanges of chemical nutrients up to the surface layers of the ocean, boosting photosynthesis and the whole trophic food chain (Morato *et al.* 2010). Their flanks are home to a wide variety of deep water corals (also known as 'cold-water corals' due to their occurrence in shallower depths at high latitudes), and gorgonians that sometimes form large canopies or reefs. These internationally protected species provide refugees and nurseries for many species of fish, crustaceans and invertebrates (Roberts *et al.* 2006). The 'services' identified for these ecosystems are largely related to artisanal or industrial fishery resources, but it is clear that these natural settings conceal treasures that are still largely unknown, including those of their biodiversity.

On continental margins, submarine canyons that cut into the shelf play a similar role as seamounts when they channel deep water upwelling (De Leo *et al.* 2010). These incised valleys can also, on the opposite, accelerate transfers of material from the continental shelf or even from continents to the deep waters.

To this must be added ecosystems that exploit the energy stored in the heart of the ocean floor as magmatic heat or hydrocarbons. Hydrothermal vent ecosystems or those associated to methane seeps have in common the local production of organic matter by chemosynthetic microorganisms from CO_2 or methane. Limited to exchange zones between the lithosphere and hydrosphere, they are home to communities as opulent as those of the most productive photosynthetic marine ecosystems. Their influence in the major ocean processes, particularly those driving the carbon cycle, remains to be quantified. This is especially the case concerning methane, a powerful greenhouse gas, which is partly sequestered under the form of carbonates at the seafloor. Although their vulnerability is not well evaluated, their patrimonial value in terms of foundamental knowledge (*e.g.* evolution of life) as well as for genetic innovations (*e.g.* bio-inspiration) is already largely recognized.

HOW CHANGES IN DEEP WATER PROPERTIES MAY DIRECTLY IMPACT ECOSYSTEMS

The temperature of the water masses that supply certain deep-sea basins has increased significantly in recent decades. For example, on the Hausgarten observatory site at the junction of the Arctic and Atlantic Oceans, an average increase of 0.1°C was observed between 2000 and 2008 at 2,500m depth (Soltwedel *et al.*, 2005). The temperature of the Eastern Mediterranean, as well, increased by 0.2°C between 1995 and 1999. Insufficient knowledge of natural fluctuations, however, limits the assessment of possible impacts. In this case, the observed warming followed a decrease of 0.4°C in the previous 4 years. Nevertheless, these observations reveal the possibility of a gradual warming of the deep water that could impact the species more severely when they are close to their tolerance; particularly in the polar regions where species have adapted to temperatures as low as -1°C at 1,000m or, to the opposite, in the Mediterranean sea where the temperature of deep waters does not drop below 12°C.

Ocean acidification, the other CO_2 problem, is even more critical as the pH of deep waters is already low due to CO_2 production from the breakdown of organic matter. Corrosive conditions for aragonite are anticipated in large regions of the deep ocean (Guinotte *et al.* 2006). These conditions would be unfavorable for the formation of skeletonnes by deep-sea corals, even if recent ex situ experiments show that their response to this constraint is complex. Similar to tropical coral reefs, the ecosystems they support could suffer major damage and will be difficult to predict, especially because they are largely out of our sight.

INDIRECT IMPACTS COMBINED WITH CARBON CYCLING AND SYNERGY EFFECTS

The biological pump that allows carbon transfer to the depths is also the main source of nutrition for abyssal communities. Changes in surface photosynthetic productivity and in the diversity of phytoplankton may affect the transfer. The relative decrease in diatoms, which larger cell size and mass favour sedimentation via a so-called ballast effect could notably reduce food inputs to the depths. A decrease in large fauna density (*e.g.* sea cucumber, echinoderms…) at the Hausgarten Arctic site, or the long-term trends at the PAP site on the Atlantic Porcupine abyssal plain, suggest that these phenomena are already occuring (Glover *et al.* 2010). In the Arctic and Antarctic regions, this phenomenon is amplified by ice melting and could significantly influence deep-sea ecosystems (Boetius *et al.* 2012).

Other indirect effects may result from the reduction of oxygen content related not only to an increase in surface photosynthetic productivity resulting in higher microbial degradation rates consuming oxygen but also to a decrease of deep water mass ventilation. For example, the deep Caribbean basin is ventilated by the transfer of cold oxygenated Atlantic waters via a sill at 1850m depth. The flow rate of these cold waters appears to have declined since the 1970s. Similarly the waters off Greenland tend to become less oxygenated, and at the same time they are warmer and saltier, reflecting a less effective ventilation (Soltwedel *et al.* 2005). The effects of a limited but persistent oxygen reduction on ocean biodiversity are poorly known. In certain cases, very poorly oxygenated waters are formed, leading to a major reduction in the depth range of the habitat for pelagic fish species like marlin and tuna (Stramma *et al.* 2010). Certain continental margins and semi-enclosed seas, such as the Black Sea, are considered as dead zones with oxygen-depleted deep waters that exclude aerobic marine organisms and especially all animal life.

CONSEQUENCES OF INTERMITTENT EVENTS UNDER ATMOSPHERIC INFLUENCE

The influence of climate on deep-sea ecosystems also occurs through intermittent phenomena that affect the circulation of water masses at local and regional scales. One of the best documented phenomenon is called 'cascading'. This phenomenon occurs irregularly and lasts several weeks. It has been described especially in the Arctic where it is linked to the formation of sea ice, and in the Mediterranean where cold, dense waters are formed in winter under the influence of winds. 'Cascades' are formed when surface waters cool down and get enriched in salt, becoming denser than deeper water. When 'flowing' into the depths, these water masses transport sediment from the shelf. These are intense events that can significantly affect ecosystems by transferring large amounts of particulate matter to the deep basins (Canals *et al.* 2006).

Changes in the intensity and frequency of these events may affect the functioning and stability of deep-sea ecosystems more rapidly than long-term changes in ocean circulation. The cycles of disturbance-recolonization due to these cascading events or other extreme events such as storms are just beginning to be described (Puscheddu *et al.* 2013, Sanchez-Vidal 2012).

DEEP SEDIMENTS: RESERVOIRS OR SOURCE OF GREENHOUSE GASES?

Continental margins are the most important ocean carbon reservoirs. Land-ocean interfaces are among the most productive marine ecosystems, and most of the carbon formed there is quickly buried in sediments. Seafloor ecosystems play a major role in this sequestration (Levin and Sibuet 2012).

The fate of fossil carbon buried in the form of hydrocarbons and, particularly, methane (as hydrates and gas) remains one of the main unknowns. The dissociation of hydrates under the effect of warming could greatly increase the concentration of GHGs in the atmosphere if methane gas is emitted massively. Conversely, methane dissolved in seawater is efficiently consumed by microorganisms in the water column and sediment. The dissociation of hydrates additionnaly affect seafloor ecosystems, through physical disturbance of the sediment (volcanic mud eruption), limiting the effectiveness of this biological filter.

A MORE DETAILED GLOBAL VIEW, BUT FEW LONG-TERM OBSERVATIONS

Given the difficulty of accessing this vast and fragmented environment where instruments are exposed to extreme physical constraints, observation data at scales relevant to climate are still sparse. However, current technologies are rapidly evolving and series of multi-annual data documenting the physical properties of water masses are becoming available through deep-sea observatories. Observations on scales representative of climatic impacts (10-50 years) are are still lacking, however.

Moreover, observation from satellites now allow more precise and detailed mapping of deep-sea 'hot-spots' and fleets of drifting buoys have brought better views of regional ocean circulation dynamics. The role of the seafloor heterogeneity and its role in carbon exchange and recycling of essential plankton nutrients (nitrogen, phosphorus, iron in particular) is being identified as essential on local scales, although the importance of this relief effect in the overall global balance has yet to be established.

Knowledge of ecological variability in the deep ocean, is still based on a limited number of data sets obtained during oceanographic expeditions. The technological advances of recent decades (ROV, AUV and HD imaging) have made these environments more accessible, and promote their exploration. A few dozen of deep sites, at most, have been the subject of multi-annual monitoring and allows a first analysis of the causes of variability (Glover *et al.* 2010).

A NEED FOR INTEGRATED EXPERIMENTAL STUDIES

To assess the impact of climate-driven disturbances, it is essential to set up observation sites and long-term experiments to investigate the synergistic effects of different phenomena on deep-sea habitats and their biological and functional diversity (Mora *et al.* 2013). On this basis it would be possible to consider mechanistic models, but this requires taking into account multiple influences on organisms and the response of whole communities to change. The latter is undoubtedly the most difficult to grasp.

The sensitivity of deep ecosystems to climate change largely depends on the plasticity of species, and particularly of the so-called foundation species or engineers of the ecosystem. The deep-sea corals for example play a major role in building reef-like structures that form the habitat for many other species. The sensitivity of these species to environmental changes is complex and in situ studies are just beginning. The acclimatation and adaptation capacities may vary from one region to another (as for example in the Red Sea where metabolic adaptations allow their development at 20° C, while elsewhere their temperature upper range is estimated to be around 13° C; Roder *et al.* 2013).

The capacity of larvae to dispersed between deep-sea hotspots, isolated in space but connected to each other by ocean water circulation, remains an enigma for most of their endemic species. Again climate change appears likely to play a role. Even if we are unable to describe the consequences of combined climate change effects, studies dedicated to the most iconic hydrothermal species are providing first insights to this issue. Sporadic events in the circulation of deep water masses induced by atmospheric events such as cyclones, for example, were only recently identified among the potential factors that play a role in larval migration at depth. Under the influence of El Nino and La Nina oscillations, it was recently shown that episodic hurricanes off Mexico generate eddies that extend from the surface to 2500m deep, promoting larval transport over distances of several hundred kilometers between usually isolated ecosystems (Adams *et al.*, 2011).

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Ocean, Biodiversity and Climate

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The marine environment has played a key role in the history of life and today's ocean continues its primordial function in the evolution of life and climate. The recognized species diversity in the oceans does not exceed 13% of all currently described living species - fewer than 250,000 - but this can be due partly to our lack of knowledge, especially concerning deep zones of the oceans and microorganisms, and partly to the fact that marine ecosystems and the way of life in such a continuous medium disperse more easily species and they are less predisposed to endemism. In contrast, marine biomass can be considerable. Climate disturbance has a direct role in the loss of biological diversity, and this loss contributes in turn to the deregulation itself.

OCEAN

The ocean is the largest living space in the world and covers at present 70.8% of the surface of the Earth – 361 million km². But we should really think of the ocean in terms of volume – around 1,370 million km³. The average depth is about 3,800m and the main feature of this gigantic environment is its continuity. Another special feature is, compared to the rest of the water on the planet, its salinity. The ocean's salinity offshore is extremely stable (35 psu[1], 1050 mOsm.l^{-1}) and the composition of ocean water is the same everywhere, as it has been for tens of millions of years.

Biodiversity cannot be likened to a simple list of species that inhabit a particular ecosystem. It is considerably more than a catalog or inventory, and in fact includes the entire set of 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 pre-biotic chemistry, built upon earlier geo-diversity, and became diversified in the ancestral ocean, around 3.9 billion years ago. Life finally appeared rather quickly, after the initial cooling and condensation of water bodies.

C. de Duve (Nobel Laureate, 1974), said in "Dust of Life" (1996) that the Earth was so ideally positioned relative to the sun, that life could not avoid appearing. And J. Monod spoke about an improbable hypothesis! The oldest known sedimentary rocks (Akilia Island, southern Greenland) containing carbon from biological origins date from 3,850 million years (Ma). Imagine the very simple, primitive life that first developed from a world of RNA and proto-cells. Current deposits of stromatolites, those rocks that precipitate bicarbonate (with beautiful deposits in Australia!) are very valuable because they contain within their silicified parts the oldest fossils of known microorganisms – cyanobacteria. These cyanobacteria began to conquer the ocean from 3,400 to 3,200Ma when there was no atmospheric oxygen. Thanks to specific intracellular pigment, and in the presence of water, photosynthesis appeared around 3,500Ma producing oxygen and sugar from light and carbon dioxide (CO_2). Oxygen then began diffusing beyond of the aquatic environment: the composition of today's atmosphere – with 21% oxygen – dates from the Cretaceous, around

1 Practical salinity unit

100Ma. In this ancient ocean, certain events occurred that proved crucial for living organisms and biodiversity:

1. The emergence of the nuclear membrane, and the individualized nucleus (prokaryote-eukaryote transition) around 2,200Ma.
2. The capture of ambient cyanobacteria that became symbionts and organelles of the cell, mitochondria and plastids, with their own little DNA, around 2,100 and 1,400Ma respectively.
3. The emergence of multicellular organisms and metazoans around 2,100Ma.

Then an exceptional event occurred in this ancient ocean: the emergence of sexuality – first in prokaryotes, later in eukaryotes. This proved vital for the explosion of biodiversity. Sexual reproduction allows for 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" among parasites and their hosts: Co-evolution, molecular dialogue, and genetic mixing eventually allow for faster "disarmament" of the parasite and a sexual selection, very different from natural selection.

The physical consequences of osmotic flux (water and electrolytes) in the marine environment led living organisms to two types of strategies:

1. In the vast majority of cases – from the first initial cell to shellfish – an intracellular, isosmotic regulation provided living organisms, separated from seawater by a biological membrane, the same osmotic pressure (about 1,000 $mOsm.l^{-1}$) on the inside (intracellular milieu and extracellular "interior") 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 to 400 $mOsm.l^{-1}$) than sea water.

The perpetual drinking behavior at sea, found in bony fish for example, associated with very active mechanisms of electrolyte excretion by the gill, 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 in order to avoid serious hydro-mineral imbalances.

Much later, during the Triassic, around 210Ma, after the third major species extinction crisis around 251 Ma, the beginnings of thermoregulation developed and found their optimal efficiency among large dinosaurs, and especially 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: just the bacteria in the sub-surface layer of the ocean accounts for over 10% of all carbon biomass of the planet. The marine environment has played a key role in the history of life, and the ocean today still has a vital role in the evolution of life and the climate.

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 – less than 250,000. This is very little, and may be explained by two things. The first is that our knowledge, especially for deep zones and for microorganisms, various bacteria and protists is still only very partial, so we significantly underestimate oceanic biodiversity. New techniques, such as coupling between flow cytometry and molecular probes, are allowing us to discover extraordinary biological diversity. At present, widespread sequencing of the ocean water mass, "random genome sequencing" (C. Venter, sequencing of all the DNA in a volume of filtered seawater) provides data that seems to be mostly unknown. The Tara Oceans expedition's circumnavigation of the world's oceans provides us with valuable information on the abundance and variety of viruses, bacteria and mainly protists. For all prokaryotes and very small eukaryotes, molecular approaches (sequencing of 16S or 18S ribosomal RNA among others) bring surprising new information every day. Moreover, and this is the second reason, it's clear that marine ecosystems and species living in a continuous medium, through the dispersal of gametes and larval stages, are less predisposed to strict endemism than in terrestrial habitats. There are many more barriers and favorable speciation isolates (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 – much more fragmented and encouraging greater speciation. The stability of the open ocean, at least for the past 100 million years, is quite extraordinary: pH, osmotic pressure and, salinity, temperature, hydrostatic pressures of the depths, dissolved gas content. Human activities are changing all this, and we will discuss this later. This stability is generating 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 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 (around 450Ma for complex metazoans). The great Permian-Triassic extinction played a key role, with 96% extinction of species, both marine and on land (around 251Ma). The explosion of flowering plant species, insects, and many other groups on Earth (around 130-110Ma) was decisive after the initial radiations (explosions in species from a single ancestor) beginning in the Devonian and especially the Carboniferous. Coevolution between plants and pollinators, and the appearance of an infinite number of new niches have often been proposed to explain the acceleration of speciation in continental environments during this period. It is also clear that the dispersion of sexual products and larvae in the sea plays an important role in the distribution of species and current bio-geography. Endemism is much more limited in the open sea, due to the stability and continuity of this gigantic environment. On land we often find species living on only a few km². No examples of marine species with such limitations are known. The enormous variety of marine modes of reproduction also take advantage of the phenomena of dispersion in water masses: males and females are not always obliged to be close! Thus, connectivity and many fewer variations in environmental factors create the great stability of the open sea, and the very specific characteristics of marine biodiversity. 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 unit of diversity, whether of an individual, a species or a population." This determines its history, past, present and future. What's more, this story is determined by processes that are themselves components of biodiversity. In fact, today we group together various approaches under this term:

1. The basic biological mechanisms that explain diversity of species and their characteristics and force us to further investigate the mechanisms of speciation and the evolution.
2. More recent and promising approaches in functional ecology and bio-complexity, including the study of matter and energy flows, and the major bio-geochemical cycles.
3. Research on things in nature considered "useful" to humanity, providing food, or highly valuable substances for medicines, cosmetics, molecular probes, or to provide ancient and innovative models for basic and applied research, in order to solve 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 the coasts, humans started collecting seafood, shells and algae, and catching fish. Just as they do agriculture on land, humans have been raising certain marine species on the coasts for at least 4,000 years old (Egypt, China, etc.). The exploitation of renewable, living aquatic resources is booming, but with serious concerns about its sustainability. The latest figures available from the FAO in 2013 (for the year 2012) gave values of 79.9 million tonnes (Mt) for marine fisheries, 11,5Mt for continental fisheries, 19 Mt for algae (including only 1Mt for harvesting at sea), and 65.6 Mt for aquaculture (including 20.3Mt at sea). The grand total – for all groups and all aquatic environments – was about 176Mt. The ocean is not only these living resources. There are also about 25,000 molecules of pharmacological or cosmetic interest, and some extraordinary, extremely relevant models for scientific research, with potential biomedical and agricultural applications. Key molecules of carcinogenesis have been discovered thanks to sea urchins and sea stars, the molecular basis of memory thanks to a sea slug and the transmission of nerve impulses thanks to the squid.

OCEAN AND CLIMATE

The ocean and the atmosphere are intimately connected and exchange energy in the form of heat and humidity. The ocean absorbs heat much more readily than ice or land surfaces, and stores energy much more efficiently. It returns the heat more slowly than the continents, and contributes to the more temperate climate of coastal areas. The ocean is thus a formidable regulator of climate. Changes in energy balance between atmosphere and ocean play an important role in climate change. Ocean circulation is affected by atmospheric circulation, and surface currents are dependent on the winds. Winds mix the surface waters down to the thermocline, below which the basic forces of circulation are related to temperature and salinity, influencing the density of water. The ocean contributes to the huge amounts of energy released at the genesis of storms and cyclones, affecting both continents and human populations. Upwellings – cold water coming up from the depths near the coasts – are rich in nutrients, profoundly altering coastal climates; taking into account their fluctuations is essential for understanding the climate system. Just the first 3 meters of the ocean store as much energy as the entire atmosphere, and the ocean has huge thermal inertia and dynamic capabilities. This 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 these capacities for storing and releasing heat. This huge reservoir of heat gives the ocean an extraordinary role in moderating climate variations. It controls the formation of wind and rain. The ocean traps and stores CO_2, thereby preventing an extreme greenhouse effect in the atmosphere. But as a result, the ocean becomes acidic, due to the production of carbonic acid. Oceanic phytoplankton also stores CO_2 in the surface layer, as do all the bio-calcifiers. 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 fluctuations in the past led to the alternation of glacial periods. The ocean plays a vital role on the climate, but the loss of biodiversity and also pollution affect the ocean and cause conditions for climate change. The amount of carbon dioxide in the atmosphere and in the ocean is increasing. Average temperatures of air in the lower layer of the atmosphere – near the land surface and near the ocean's surface – are rising. And average sea level is rising faster than ever since the end of the last ice age. Rapid changes in the chemical composition of sea water have a harmful effect on ocean ecosystems that are already stressed by overfishing and pollution.

Climate change has a direct role in the loss of biological diversity, but this loss contributes in turn to the very problem! Biodiversity loss severely affects climate change! Phytoplanktonic chains in the sea are deeply influenced by climate change and their changes affect in return the capacity of the ocean to dissolve CO_2. Moreover, let's not forget that the effects of rapid climate change are added to other severe problems: destruction and pollution of the coasts, accelerating systematic exploitation of living resources, and the uncontrolled spread of species (including from the ballasts of large ships). That's a lot for biodiversity to handle!

Coral Reefs and Climate Change

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Coral reefs are found in only a small percentage of global oceans, between 0.08 and 0.16,%, but they shelter about one third of the marine species known today. This ecological success is due to a symbiosis between a coral and an intracellular microalgae, commonly called zooxanthellae. "Organismic engineers", they are the source of the largest biological constructions on the planet. Genuine oases of life, they support the direct sustenance of more than 500 million people in the world from fishing, but they engage human interest also for other reasons: protection of coasts against erosion, high value tourist areas… Ecological services from coral reefs are estimated at approximately 30 billion USD per year. Their growth is dependent on many factors (light, temperature, pH, nutrients, turbidity…). They are therefore extremely sensitive to the current changes in our environment: water temperature variability, ocean acidification, in addition to localized disruptions (pollution, sedimentation, coastal development, overfishing, marine shipping…). An increase of less than 1 degree above a threshold value is sufficient to cause bleaching. It breaks the coral symbiosis with their zooxanthellae throughout the populations, leading to the disappearance of the reef. Similarly, ocean acidification disrupts the formation of a coral's skeleton, and many other biological functions such as reproduction. We actually estimate that approximately 20% of the global coral reefs have already disappeared completely; 25% are in high danger; and 25% more will be threatened by 2050 if positive management action is not taken.

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 buildup of calcareous skeletonnes of marine organisms called reef-building corals (Cnidaria, Scleractinia). They are cemented together by the biological activity of calcareous organisms (macroalgae, sponges, worms, molluscs…). Corals are named "engineering organisms", while the reef is considered "biogenic" because they are the result of biological activity. Coral reefs therefore represent ecosystems that have been built by their own inhabitants.

The total area covered by coral reefs varies, depending on the calculation methods, between 284,300km² (Smith, 1978) and 617,000km² (Spalding *et al.*, 2001), therefore covering between 0.08 and 0.16% of the surface of the ocean. French reefs alone cover an area of 55,557km². The largest reef is the Great Barrier Reef which runs along the north-eastern coast of Northern Australia over a distance of 2300 km. It is reputed to be the only animal construction visible from space. The second largest reef is French, the New Caledonian barrier, which is 1600 km long. These two barrier reefs have been registered by the UNESCO World Heritage (respectively in 1981 and 2008).

Coral reefs come in different shapes and sizes, the first published description dating from Charles Darwin during his voyage on the Beagle (Darwin, 1842):

- Fringing reefs: They follow the coastline, maintaining an active growth area offshore and an accumulation of dead coral inshore, 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. In this way, the lagoon becomes larger and the reef can reach up to 1km away from the coast.
- Atolls: these are the ultimate step in the evolution of a reef, where the island has completely disappeared below the sea surface. Atolls preserve the initial circular shape of the island. There are approximately 400 atolls in the world.

Reef growth is of the order of about 4kg of calcium carbonate ($CaCO_3$) per m² per year (Smith & Kinsey, 1976), but values can vary considerably from one reef to another, in some cases reaching up to 35kg $CaCO_3$/m²/year (Barnes & Chalker, 1990), *i.e.* a vertical annual growth rate of 1 to 7mm. Many factors influence these growth rates: light, temperature (optimal between 22° and 29°C), nutrients, currents, turbidity, pH and the saturation state of calcium carbonate in the seawater…

The formation of calcium carbonate by reef-building organisms causes the release of carbon dioxide into the surrounding environment. Hence, contrary to what has been believed, a reef mainly dominated by coral acts as a minor source and not as a sink of CO_2 (about 1.5mmol CO_2/m² day. Tambutté *et al.*, 2011 for a review). Nevertheless, reefs still do play an important role as a carbon sink (as $CaCO_3$), with rates of the order of 70 to 90 million tonnes of carbon per year (Frankignoulle & Gattuso, 1993).

CORALS, AT THE ORIGIN OF THE REEF

Reefs are mainly built by corals. Formerly known as stony corals, reef-building corals are now included in the Order of Scleractinians (subclass *Hexacorallia*, class *Anthozoa* of phylum *Cnidaria*). Among the *Scleractinia*, about half the amount of species (about 660 out of 1,482 species known to date, Cairns, 1999) are involved in reef construction. These are called hermatypic. They consist of polyps of variable sizes, depending on the species, and form functional units. Each polyp has a mouth surrounded by tentacles. The polyps are connected to each other by network of cavities, the coelenteron, which covers the coral tissue. The whole assemblage is known as colonial (even though the colony functions as a single organism) while individual corals are called modular animals. They present various shapes and sizes, depending on whether the species are branching coral, blade coral, encrusting, or massive coral for example, and show growth rates that can exceed 15cm per year of axial growth in their natural environment (Dullo, 2005). The size of certain massive corals may even exceed 6m in diameter.

The degree of success for a reef to develop and to thrive is mainly related to the capability of the majority of scleractinian corals (just under 900 species, Michel Pichon, Comm. Pers.) to establish a mutual symbiosis with photosynthetic dinoflagellates commonly called *zooxanthellae* (*e.g. Symbiodinium sp.*). These microalgae reside inside the coral's gastroderm, isolated from the animal's cytoplasm by a perisymbiotic membrane that regulates the exchanges between the symbionts and the host (Furla *et al.*, 2011 for a review). These two partners have co-evolved since the Triassic (Muscatine *et al.*, 2005), developing unique abilities (*e.g.* the ability for the hosts to actively absorb CO_2 and nutrients and to protect themselves from ultraviolet rays, hyperoxia and oxidative stress; the ability of the algal symbiont to exchange nutrients with its host; Furla *et al.*, 2005, 2011). Due to the presence of zooxanthellae, the distribution of corals at depth is dependent upon light availability (generally between 0 and 30m depth). Thanks to modern sequencing techniques, a strong diversity in bacteria has been evidenced inside corals. These bacteria appear to play an important physiological role. The entire community of these living organisms forms a functional unit called a holobiont, often referred to as a super-organism.

Symbiont photosynthesis is also related to another function of coral, biomineralization, that is to say its ability to build a limestone or biomineral skeleton. The property of a biomineral is that it is a composite material, comprising both a mineral fraction and an organic fraction. Even though the latter is minimal (<1% by weight), it plays a key role in controlling the deposition of calcium carbonate in the form of aragonite (German *et al.*, 2011, Tambutté *et al.*, 2008, 2011). Using mechanisms that are still a matter of debate, light, via symbiont photosynthesis, has been observed to stimulate the calcification of coral by a factor reaching 127 in comparison to night calcification. However, in most cases, this factor varies between 1 and 5, with an average value of 4 (Gattuso *et al.*, 1999).

Coral reproduction is typically sexual and involves a larval stage called *planula* which ensures the species dispersion. They can also have a high asexual reproductive capacity by fragmentation. This capacity is utilized in the development of *ex situ* cultures.

CORAL AND CORALS

Coral, in its name, hides many organisms belonging to the *Cnidaria* phylum and is at the base of particular ecosystems:

- Cold-water corals, also called deep-sea corals: these corals belong to the same order of cnidarians as reef-building corals. Like them, they are engineering organisms, capable of building a rich ecosystem that provides habitat for many other creatures in the deep waters of the Atlantic, Pacific, as well as the Mediterranean Sea. Unlike their surface water cousins, they are acclimated to cold waters (6° -14°C) and do not host photosynthetic algae. These reefs therefore play a significant role as shelters and nursery areas for many species of fish of commercial interest (Roberts *et al.*, 2009).
- The coralligenous in the Mediterranean: they are formed by an assemblage of stationary creatures (*e.g.* gorgonians, red coral, encrusting calcareous algae…). The coralligenous in the Mediterranean form a very rich coastal ecosystem, especially along underwater cliffs. It is of particular interest both for fishing and aquatic tourism (RAC/SPA 2003).

THE CORAL REEF: A BIODIVERSITY HOT-SPOT

The ability to live in symbiosis with dinoflagellates has allowed coral reefs to build large constructions in usually oligotrophic conditions, that is to say, nutrient-poor waters. Coral reefs have existed since the Triassic, about 200 million years ago. However, since that time there have been many phases of disappearance/reappearance. The development of the Great Barrier Reef seems to have begun 20 million years ago. However, primitive forms that are different from modern corals, have existed long before the Triassic, during the Devonian about 400 million years ago.
Coral reefs are home to the greatest biodiversity on Earth with 32 of the 34 animal phyla known to date and include a third of marine species known so far, representing nearly 100,000 species (Porter & Tougas, 2001). Hence, 30% of the known marine biodiversity is sheltered in less than 0.2% of the total surface of the oceans! In the marine environment, they therefore represent the equivalent of the primary tropical forests. For comparison, the number of species of molluscs found on 10 m² of reef in the South Pacific is greater than what has been acknowledged throughout the whole North Sea. As another example, in New Caledonia there are over 400 species of coastal nudibranchs while in mainland France there is little more than a dozen species for an equivalent coastline.

This "biodiversity" is however not homogeneous between reefs. Indeed, there is a skewed distribution of the diversity and abundance of corals between the Atlantic and Pacific Oceans, as well as within these oceans. In these two oceans, the diversity and abundance are concentrated in the western parts: the Coral Triangle (also called " Centre for Coral Biodiversity ") in the Pacific, including the -Indonesia Malaysia - Philippines - China Sea - Solomon Islands region; the

Caribbean in the Atlantic. There is also a strong east-west longitudinal gradient. The fauna and flora associated with reefs generally follow similar gradients.

THE CORAL REEF: AN EXCEPTIONAL WEALTH FOR MANKIND

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, just as much in terms of a food resources, coastal protection and tourism... Approximately 275 million people worldwide live within 30km of a coral reef and the livelihood of over 500 million people directly depend on reefs. On one hand economists estimate that the annual value of the benefits provided by the reefs is worth slightly more than 24 billion euros (Chen *et al.*, 2015). On another hand, the TEEB report (TEEB, 2010) has estimated that the destruction of coral reefs would represent a loss of about € 140 billion per year.

The ecosystemic benefits provided by coral reefs include:

1. Natural resources

- Food: coral reefs provide 9 to 12% of the world catch of edible fish and 20 to 25% of the fish catch in developing countries (Moberg & Folke, 1999). This figure reaches 70 to 90% for the South East Asian countries (Garcia & de Leiva Moreno, 2003). The total estimated income of reef fisheries is about 5 billion euros (Conservation International, 2008). Most of these fisheries are traditional, carried out on foot by the local population, especially women and children who collect fish, molluscs (clams), crustaceans (crabs and lobsters) and sea cucumber (also referred to as trepang). A healthy reef is estimated to annually provide 5 to 10 tonnes of fish and invertebrates per km2.
- Mineral resources: coral reefs provide housing construction materials (Maldives, Indonesia), sand for the construction of roads or fertilizers for agricultural land. Coral reefs in the Maldives thus supply about 20,000m^3 of material annually (Moberg & Folke, 1999).
- Live Resources: beyond fishing for food needs, reefs also represent a fishing reserve for coral reef aquariology (15 million fish per year for 2 million aquarists in the world) and pearl farming, etc.

2. Conservation

- Coastal Protection: coral reefs have an undeniable role in the protection of coastline 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 90% of the impact load of a wave (Wells, 2006). During the devastating 2004 tsunami in the Indian Ocean, coasts protected by healthy coral reefs were much less affected by the deadly wave. The value of coastal protection against natural disasters has been estimated to lie between 20,000 and 27,000 euros per year per hectare of coral (TEEB, 2010). The total profit is estimated at 7 billion euros per year (Conservation International, 2008).

3. Cultural resources

- Tourism: tourists are attracted to the natural beauty of coral reefs (via terrestrial tourism, diving). The large number of visitors promotes employment, a windfall for the poverty-stricken parts of the world. For example, the Australian Great Barrier Reef attracts about 2 million visitors annually, producing an income of around 4 billion Euros for the Australian economy and 54,000 jobs (Biggs, 2011). According to estimates compiled by the TEEB report, one hectare of coral reef represents a yearly profit of 64,000 to 80,000 Euros from tourism and recreational opportunities. Ecotourism alone earned 800,000 euros per year in the Caribbean. The total annual income from coral reefs is estimated around 8 billion euros (Conservation International, 2008).
- Cultural or religious heritage: Coral reefs are at the base of many cultural and religious traditions. In southern Kenya, for example, many religious rituals are structured around coral reefs in order to appease the spirits (Moberg & Folke, 1999).

- Medical resources: the numerous marine invertebrates (sponges, molluscs or soft corals) represent a potential supply of new drugs for human health. Coral is also starting to be used as a biological model to better understand immunity or aging mechanisms (Moberg & Folke, 1999).

THE CORAL REEF: LOCAL AND GLOBAL THREATS

The coral reef ecosystems are currently threatened both locally (pollution, sedimentation, unsustainable coastal development, nutrient enrichment, overfishing, use of destructive fishing methods…) and, since the 1980s, globally (global warming, ocean acidification). The Global Coral Reef Monitoring Network (GCRMN) estimates that at present, 19% of reefs have been destroyed, 15% are seriously damaged and may disappear within the next ten years, and 20% could disappear within less than 40 years. More positively, 46% of the world's reefs are still healthy (Wilkinson, 2008). The rare monitoring studies on reef growth show a clear long-term decrease in coral cover: in an analysis of 2258 measurements from 214 reefs of the Great Barrier during the 1985-2012 period, De'ath *et al.*, (2012) evidenced a decline in the coral cover from 28.0% to 13.8% as well as loss of 50.7% of initial coral cover.

Among the global events that affect coral reefs, the increasing temperature of surface water is causing a widespread phenomenon, coral bleaching. Unique example, visible to the naked eye, of the impact of climate change on an ecosystem, coral bleaching is the result of the rupture of the symbiosis between corals and zooxanthellae symbionts. Although it can be reversible during the first few days, this bleaching effect inevitably leads to coral death a few weeks after the symbiosis is halted (Hoegh-Guldberg, 1999; Weis & Allemand, 2009). This phenomenon, whose inner mechanisms are still under debate, usually occurs when the temperature exceeds a certain threshold by 0.5°C.

A second event is just as seriously affecting coral biology: ocean acidification, also referred to as the other effect of CO_2 (Doney *et al.*, 2009). Part of the excess carbon dioxide produced by human activities dissolves into the oceans, reducing on one hand the greenhouse effect (and thus reducing the increase in global temperature), but on the other hand causing a increasing acidity of the oceans, according to the following reaction:

$$H_2O + CO_2 \longleftrightarrow HCO_3^- + H^+$$

To date, the pH of seawater has decreased by about 0.1 units since the beginning of last century (from 8.2 to 8.1) which corresponds to an increase in the acidity of the water by about 30% (Gattuso & Hansson, 2011). Acidification primarily affects the calcification rates of corals, and therefore reef growth. However, it appears that the effects vary greatly from one species to another (Erez *et al.*, 2011). The differences in sensitivity may be due to a differential ability of the animal to control the pH of its calcification site (Holcomb *et al.*, 2014; Venn *et al.*, 2013). However the increase in dissolved CO_2 has also been found to cause 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 the physiology of these creatures is too insufficient to predict whether corals will be able to adapt to rapid changes in the environment, especially since earlier studies suggest that the combined effects of the decrease in the pH with the increase in temperature of the sea seem to have cumulative effects (Reynaud *et al.*, 2003).

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Exploited Marine Biodiversity and Climate Change

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Climate change is affecting the productivity of marine ecosystems and impacts fishing, while the 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 renewable resources most transacted in the world. Changes in physico-chemical characteristics of seawater affect the metabolism of individuals, the life cycles of species, relationships between predators and prey, and modification of habitats. Geographic distributions of fish (displacement rate towards the poles is 72.0 ± 13.5km/decade) and the dynamics of ecosystems could undergo profound disturbances in the coming decades, affecting fisheries globally and jeopardizing food security in many southern countries. The maintenance of healthy and productive marine ecosystems is a critical issue.

THE CHALLENGES IN MARINE FISHERIES

Climate change is affecting the productivity of marine ecosystems with an impact on fisheries. Fisheries represent the last human activity that is exploiting, at an industrial scale, a wild resource that is sensitive to environmental fluctuations. Population growth and changes in food habits have led to an increasing demand for fish for human consumption. Fish has become the main source of animal protein for a billion people worldwide. It is also one of the most traded global renewable resources: 28 million tones 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 it appears that the geographical distribution of fish and ecosystem dynamics are to undergo profound disruptions in the coming decades thus affecting fisheries worldwide, and jeopardizing food security in many countries of the southern hemisphere (Lam *et al.*, 2012).

THE EFFECTS OF CLIMATE CHANGE ON MARINE BIODIVERSITY

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

The disturbances are now clearly established across a wide range of taxonomic groups ranging from plankton to top predators and in agreement with the theoretical approaches regarding 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 accordance with the expected responses in a context of climate change (Poloczanska, 2013). A large number of biological events concerning maximal phytoplankton abundance as well as reproduction and migration of invertebrates, fish and seabirds, all take place earlier in the year. Hence, since the past fifty years, the Spring events have been shifting earlier for many species by an average of 4.4 ± 0.7 days per decade and the summer events by 4.4 ± 1.1 days per decade. Observations show that for all taxonomic groups, but with great heterogeneity, the rate of displacement 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 or the North Sea. The observed modifications in the distribution of benthic fish and shellfish with latitude and depth can be mainly explained by changes in the temperature of the sea (Pinsky *et al.*, 2013). The migration rates recorded in the marine environment appear to be faster than observed in the terrestrial environment.

THE IMPACT ON FISHERIES AND GLOBAL FOOD SECURITY

As mentioned above, fish and marine 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 capture potential for the stock of 1066 species of marine fish and invertebrates exploited between 2005 and 2055 can be predicted according to different climate change scenarios. According to these studies (Cheung *et al.*, 2009), climate change may lead to a large-scale redistribution of the overall catch potential, with an average increase of 30 to 70% in high-latitude regions and a drop reaching 40% in the tropics. Among the 20 most important fishing areas of the Exclusive Economic Zone (EEZ) in terms of landings, ZEE regions with the highest increase in the potential catches in 2055 should be Norway, Greenland, the United States (Alaska) and Russia (Asia). On the contrary, the EEZ areas with the greatest loss of maximum catch potential should include Indonesia, the United States (except Alaska and Hawaii), Chile and China. Many severely affected areas would be located in the tropics and would be socio-economically vulnerable to these changes.

Further studies, taking into account factors other than the temperature of the oceans, highlight the sensitivity of marine ecosystems to biogeochemical change and the need to take into account the 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 catchability of 120 species of fish and demersal invertebrates exploited in the North Atlantic show that ocean acidification and decreasing oxygen concentrations could reduce the growth performance and lower the estimated catch potentials from 20 to 30% (10-year average for 2050 compared to 2005) in comparison with simulations that do not take these disturbing factors into account. In addition, changes in the phytoplankton community structure could also reduce the predicted catch potential by ~ 10%. All these results highlight the sensitivity of marine ecosystems to biogeochemical changes (Cheung *et al.*, 2011).

The observed changes are now noticeable in the species composition of catches between 1970 and 2006 which are largely attributed to global long-term ocean warming (Cheung *et* *al.*, 2013). Modifications in the marine environment should continue to generate considerable challenges and costs for human societies worldwide, particularly for developing countries (Hoegh-Guldberg & Bruno, 2010).

HOW TO LIMIT THE EFFECTS OF CLIMATE CHANGE ON MARINE ECOSYSTEMS?

The best way to fight against the effects of climate change is to preserve biodiversity and avoid overexploitation of certain species. The latter has been admitted as an aggravating factor on the effects of climate change (Perry *et al.*, 2010). An objective of the Ecosystem Approach to Fisheries (EAF) is to reconcile exploitation and conservation of species; in other words it would allow to maintain the integrity and resilience of ecosystems. The EAF contributes to the crucial issue of maintaining marine ecosystems healthy and productive, while proposing a new manner of considering fish exploitation in a broader context (www.fao.org/Fishery/eaf-net). The need to develop an adaptation policy that could minimize the impacts of climate change through fishing must become a priority. This would require better anticipation of changes using predictive scenarios (*sensu* 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. Although the impact of climate change remains most of the time unavoidable, the adaptation of communities to rapid changes are yet to be understood and assessed, thus opening many research perspectives on this subject.

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Aquaculture and Global Changes

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Aquaculture, a booming sector, now provides almost half of the fish and shellfish on world markets. Climate change will certainly affect aquaculture productions, however the scale is not presently quantifiable given the uncertainty of global models. Impacts will vary by region and type of production. Adaptation of production systems is potentially feasible through actions of all stakeholders involved. Direct impacts will be related to changes in production conditions in freshwater, brackish water and marine environments. The main indirect impact will probably be related to the dependence on an exogenous food supply for the cultivated organisms. However, the negative impacts (eutrophication of inland waters, ocean acidification…) and positive impacts (aquaculture activities in colder areas, better growth of farmed organisms…) could balance out.

At present, aquaculture is booming while global fishing statistics remain stationary. This ancient activity, close to agriculture, consists of animal or plant production in aquatic environments. It has been growing exponentially since the 1980s and now supplies almost more than half of the fish and shellfish for the global market.

It is clear that aquaculture will be severely impacted by climate change. Various publications on this issue state that the forecasted global environmental conditions will affect the aquaculture sector. It is important to note, however, that all the predicted impacts will not necessarily be negative. Indeed, climate change should potentially create development opportunities for countries or regions where current production is low.

In aquaculture, unlike fisheries, human intervention is present throughout the life cycle (with certain exceptions). This therefore allows actors to potentially take actions to adapt to climate change. The success of the adjustments made will depend upon the severity of environmental conditions, the costs and coping capacities of the actors in the field but also upon national and international decision-makers.

DIRECT RISKS OF GLOBAL CHANGE ON AQUACULTURE

In 2012, Global aquaculture production reached a record high of 90.4 million tonnes (fresh weight equivalent; valued at 144.4 billion US dollars), 66.6 million tonnes of which was edible products (137.7 billion US dollars) as well as 23.8 million tonnes coming from aquatic plants (mainly algae; valued at 6.4 billion US dollars). Climate change will threaten certain aquaculture activities but the extent of these impacts cannot yet be quantified in the absence of global models that can take into account all direct and indirect effects of global changes. However, one thing is for certain: there will be consequences on production, which in turn will affect humans. The global demand for fisheries and aquaculture products is the largest of all animal food products (26.85 to 27.45 million tonnes vs. 20.38 to 21.99 million tonnes in 2009). Moreover, aquaculture products are an important source of nutrition for developed and developing countries (viz. a contribution to food security), and represent a source of income for all communities, regardless of the standard of living. Among the impacts of climate change that will affect aquaculture, direct impacts will mainly be related to modification of production conditions. Average production will thus be affected, not only in the marine environment (Table) but also in inland areas (fresh and brackish waters) where the majority of global production is concentrated. These inland areas are more sensitive to changes, in fact, it is expected that global warming and the resulting global surface water temperature rise will impact aquaculture more significantly in these areas than in the marine environment (due to the modification of the optimal temperature range of organisms that are currently cultivated).

Nevertheless, the negative and positive impacts could balance out. Amongst positive impacts of climate change, scientific models predict an expansion of aquaculture activities towards cooler parts of the world, which will have longer thawing periods, better growth rates of cultured organisms,

Table - Synthesis of climate change impacts on oceans and coastal areas of climate change that will affect aquaculture (from Allison *et al.*, 2011):

- Change in temperature
- Change in salinity, density and stratification of the oceans
- 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
- The timing and success of physiological processes, spawning and recruitment
- Primary production
- Changes in the distribution of marine life
- Changes in abundance of marine life
- Phenomenological changes (*i.e.* duration of lifecycles stages)
- Invasion of species and diseases
- Changes in regime and extreme events

and an improved capacity of food conversion for the latter. However, these positive effects will be concurrent with negative impacts (*e.g.* increased eutrophication in inland waters, ocean acidification). In both cases (negative or positive effects), production methods must be adapted.

DIVERSE VULNERABILITIES AND DIFFERENT TYPES OF PRODUCTION

Aquaculture is not practiced uniformly throughout the world. This heterogeneity must be considered in order to obtain for a meaningful assessment of the potential impacts of climate change. Climate change is likely to occur with differing intensities depending on the geographical position, thus resulting in different impacts. It is therefore necessary to keep in mind that aquaculture exists mainly under three climatic regimes (tropical, subtropical and temperate), in three types of environment (seawater, freshwater and brackish water) and covers a wide range of taxa. In terms of different taxa, it is clear that some species are more tolerant than others to changes and that some will be more likely to undergo specific changes (for example, ocean acidification should essentially affect calcifying organisms such as bivalves whose production was 14 million tonnes in 2012).

Asia alone accounts for approximately 90% of global aquaculture production, China being the major producer with a fish production accounting for nearly two-thirds of world production and contributing significantly to the nutrition of the Chinese population. Asian aquaculture production is characterized by a diversity of species and production systems used. However, inland aquaculture (fresh or brackish water) still dominates the production of the continent whereas fish mariculture is underexploited, unlike some other countries or regions that almost exclusively rely on this type of aquaculture (*e.g.* salmon farming in Norway).

In Asia, direct impacts only related to global warming are likely to be beneficial, resulting in better growth rates of cultured stocks. However this should not conceal the impacts of climate change on water availability, worsening weather conditions such as extreme rainfall, increasing eutrophication, sea level rise and stratification of the oceans.

The intensification of aquaculture in certain areas (namely Asia and tropical zones) motivates the development of adaptation strategies to mitigate the impacts of climate change in these areas, especially if the expected difference between demand and supply of aquatic products for consumption needs to be compensated through aquaculture.

Among the different global changes, one is regularly highlighted as its impacts are already being felt on shellfish production on the West Coast of the United States: ocean acidification. Associated adverse effects are, for the moment, well documented for two key product groups in aquaculture: bivalves and crustaceans. The increased presence of dissolved CO_2 in seawater can impact marine life at 3 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.
3. An increase in the partial pressure of CO_2 in organisms, which would result in a hypercapnia.

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 on fish production will be: heat stress, increased oxygen demand, aggravation of the toxicity of pollutants, higher incidence of fish diseases. More generally, production systems will be affected by a decrease in the solubility of oxygen in a warmed ocean, eutrophication, stratification, uncertain water supplies and salt water intrusion due to rising sea levels.

The impacts on the production of shellfish and therefore the socio-economic impacts will be significant. In 2012, although farmed shellfish only accounted for a volume of 9.7% (6.4 million tonnes) of the total aquaculture production for human consumption, it represented a value of 22.4% (30.9 billion U.S. dollars). Mollusc production however (15.2 million tonnes), although producing more than twofold that of crustaceans. There have been attempts to adapt to these impacts of climate change on different production systems including the use of cages or closed systems.

INDIRECT RISKS OF GLOBAL CHANGE ON AQUACULTURE

The impacts of climate change are not just limited to the environment of the production site. The conditions will foster, in particular, the remobilization of contaminants that are currently non-bioavailable, the emergence of diseases, increased toxic algal blooms, the disappearance of key species (*e.g.* for 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 will o doubt be linked to the dependence of aquaculture on external food supplies. 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 felt most keenly in the temperate regions where fish farming is entirely based on carnivorous species but they should also affect other areas, as the vast majority of countries involved in aquaculture production uses 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 (ENSO). There is a strong relationship between trends in 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 thus 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 certain inputs used in aquaculture by the fisheries industry, including fishmeal, fish oils and to a lesser extent, juvenile organisms. The impacts of climate change on fisheries worldwide will therefore have effects 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 face unexpected shocks has already been proven. In particular, this can be illustrated by the short time it took for most of Asia to change the species of shrimp 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 very quickly resumed normal production.

Despite these advantages, the aquaculture sector must prepare itself. Advances and development of models and long term predictions are needed to address the multiple and complex impacts of climate change. Moreover, progress in the selection of species that are better adapted to cope with predicted conditions (to multiple stressors) along with a conceptualisation of adaptation solutions for cultivation practices are needed.

Additionally, it is important that the development of aquaculture practices should be as environmentally friendly as possible, involving the efficient use of resources like water, land, energy and nutrients in agricultural systems. Improvements in the formulation of feed are in progress and should ideally include ingredients derived from alternatives marine resources (such as by-products from fish filleting factories). More environmentally friendly aquaculture could also utilize a certification program but even though these programs do exist, the concept of sustainable aquaculture is still under debate. However, the current situation is not as bad as what has been relayed by the media. Even though the current production practices are far from perfect, they are generally more efficient in terms of product produced per unit of food input than other land-based animal production systems. Furthermore, the amount of environmental degradation caused by aquaculture is less than most agricultural counterparts. These conclusions in the media are almost always based on high-value aquaculture products such as shrimps and carnivorous fish like salmon, hence leading to false ideas among the public, planners, developers and investors. In reality, the vast majority of aquaculture is still dependent 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 on 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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Small Islands, Ocean and Climate

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The physical characteristics of small islands (limited land area, small plains, high exposure to unpredictable marine weather) 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 iconic figures representing the threats associated with climate change: rising sea levels, increase in cyclones, as well as ocean warming and acidification. Although a wide diversity of answers is to be expected from on island system to another, Small islands in general have to face urges threats: reduction in islands'surface area, increase in coastal erosion, degradation of coral reefs and mangroves. The impact on land (soil, water, flora and fauna) and marine resources (reefs and fisheries) will be major, hampering the future of human survival in many islands. The challenge such societies have to face is thus extremely urge.

Regardless of their political status, small islands, whether isolated or part of an archipelago[1], have to face a number of constraints inherent to their small size (areas 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, the education system, etc.). In particular, their geographical characteristics (limited land area, reduced plains, strong exposure to sea-related hazards) and human specificities (strong dependence upon subsistence activities and ecosystems) can explain their high sensitivity to environmental changes and to natural disasters. Such features directly generate a series of impacts which, on the continent, would generally be easily attenuated in space and in time (Duvat and Magnan, 2012).

Small islands are territorial systems that are both vulnerable and reactive, placing them at the forefront of the consequences of environmental changes. Among the changes consecutive to the excess of anthropogenic greenhouse gases in the atmosphere, they are particularly disturbed by those affecting the global ocean (surface water warming together with acidification). The political representatives of these insular territories often even present their islands as "the first victims of climate change." The threats to small islands are not as marginal as have been supposed, since they are, in a certain way, the same as those faced by the vast majority of the world's coastlines. Therefore, beyond their specificities, there are lessons to learn from these "miniature lands".

This article follows the simple logic of the 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

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

and their relationship to the processes of "unsustainable development[2]" will then be addressed, and finally, a few key messages will conclude.

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 progressive degradation of vital resources like fresh water or the occurrence of devastating extreme events like cyclones, raise the question of their chances of survival on the horizon over the next 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 reasons, which are directly related to the anthropogenic emissions of greenhouse gases since nearly 150 years and that can be classified into four categories: rising sea level, extreme events, warming ocean waters and acidification of the global ocean.

Rising sea level

Rising sea level as a consequence of climate change is undoubtedly the most publicized phenomenon, especially for small islands. Catastrophic interpretations badly relay the more prudent scientific conclusions, and certain media announce the impending disappearance of low-lying islands (especially the Maldives, Kiribati and Tuvalu) while others proclaim the imminent flooding of coastal plains that concentrate populations and economic activities. Although such claims can be questionable, because the responses of island systems to climate pressure will be necessarily diverse, it remains an undeniable fact that the sea level has been rising for more than a century due to anthropogenic climate change. Why? First, the increase in the temperature of the lower layers of the atmosphere warms the surface ocean waters, resulting in their expansion. This is combined to the melting of continental ice (mountain glaciers, Arctic and Antarctic ice caps), increasing the volume of ocean water, which, schematically, tends to "overflow". The average rate of sea level rise was 17cm across the globe throughout the twentieth century, corresponding to about 1.7mm/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 sea level rises, with values reaching for example + 5mm / year in Funafuti (Tuvalu) (Becker *et al.*, 2012). Secondly, the scientific community points out that the sea level rise, which has accelerated since the early 1990s[3], will continue over the next century. The worst case scenario[4] predicts an average increase in the sea level of + 45 to + 82cm between now and 2100 (Church *et al.*, 2013). Furthermore this trend is irreversible partly because of the latency phenomena that characterize the oceanic and atmospheric processes. These will cause the sea level to carry on rising at least during 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 rise in sea level will be all the more serious for small islands as they have a high coastal index (coastline to land area ratio) and as 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 (Pacific Central) will be illustrated in the following.

In 1989, the United Nations adopted a specific resolution on the adverse effects of rising sea levels on islands and coastal zones, officially recognizing the high vulnerability of these territories to climate change. A few years later, the United Nations Conference on Environment and Develop-

2 Term that describes the unsustainable development models that are currently used.

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

4 Models that are the basis of the last IPCC report considered 4 main scenarios concerning greenhouse gas concentrations in the atmosphere by the end of the century. These scenarios are Representative Concentration Pathways (RCP), ranging from the most optimistic (RCP2.6) to the most pessimistic (RCP8.5).

ment (Earth Summit, Rio, 1992) emphasized once again the particular case of small islands. Most 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 level.

Extreme events: hurricanes, distant waves and El Niño

Our understanding of the interactions between the ocean and the atmosphere is still incomplete and limits our ability to model certain climate phenomena, and therefore to forecast the evolution of extreme events (storms and El Niño). However it is foreseeable that the pressure of these extreme events on small islands is going to increase.

The energy in tropical cyclones is far greater than that of temperate depressions, with wind speeds that can exceed 350km/h. These winds can destroy the vegetation, infrastructure and buildings. Along with cyclones, heavy rainfall often occurs (up to 1500mm in 24h) leading to overflowing riverbeds and even catastrophic flooding. In addition to these weather effects, cyclonic swell can impact coastal areas, causing even more destruction than cyclones associated to storm surges[5]. The consequences of marine inundation (waves + storm surge) are obviously amplified when it combines with flooding from inland waterways. Cyclonic swell, which often reaches a height of 4-6m at the coast, can also cause marked erosion peaks (retreat of the coastline by 10 to 15m, lowering of the foreshore), or on the contrary, a strong accretion along the coast due to the accumulation of sand and blocks of coral torn from the reef (Etienne, 2012).

Given the complexity of 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 last IPCC report, the main facts to bear in mind are that: *(i)* the frequency of cyclones should not inexorably increase in the future; *(ii)* the most intense cyclones are expected to increase in intensity, at least in certain regions; *(iii)* the trajectories, *i.e.* the impact areas of cyclones, are very likely to evolve in the future. On this basis, and despite the uncertainties about the evolution of cyclones, an increase in the destructive impacts of cyclones should be expected in small islands: firstly, because the rise in sea level will allow cyclonic swell to propagate farther inland; and secondly, because the intensification of the most powerful cyclones will worsen their destructive effects on coastal areas in certain regions. For example, erosion is expected to accelerate in places where cyclones are already causing erosion peaks.

Likewise, the evolution of storms in temperate zones (North and South) and at high latitudes, which remains difficult to predict, should also have an impact on the changes in the sea-related hazards in insular environments. Indeed, it is now clear that the powerful swell produced by these storms can spread over great distances across the ocean and cause significant damage on distant island territories thousands of kilometers from its area of formation (Nurse *et al.*, 2014). For example, in December 2008, distant swells caused significant damage in many states of the Western Pacific like 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, while at least four of its manifestations are known to disrupt insular environments. Firstly, the significant changes in surface ocean temperatures that occur during El Niño events are reflected in some regions by marked temperature peaks. They are responsible for devastating coral bleaching events[6] (95 to 100% coral mortality in the Maldives and the Seychelles in 1997-1998). Secondly, El Niño events result in an increase in the number of cyclones in areas usually less exposed, as is the case of the Tuamotu Archipelago in French Polynesia: while the

5 Abnormal increase in the sea level due to low atmospheric pressure (-1mb = +1cm) and to wind stress (accumulation of water on the coastline), that add to the wave action (upwash and backwash on the shore).

6 When the temperature tolerance threshold of coral, around 30°C, is exceeded, the coral expulse the zooxanthella (symbiotic, photosynthetic algae that partly feed the coral), discolour, and are likely to die massively. A prolonged bleaching can lead to the death of a whole reef.

frequency of cyclones is normally 1 every 20 to 25 years, 5 cyclones have passed the northwestern islands of this archipelago within six months during the 1982-1983 El Niño (Dupont, 1987). Thirdly, El Niño causes major disruptions in rainfall patterns, causing heavy rains in certain areas (central and eastern Pacific) and pronounced droughts in others (western Pacific, with strong impacts in Kiribati and in the Marshall Islands, for example). Some islands, such as the south of Kiribati for example, can thus experience a drought period of 1 to 2 years. Finally, El Niño events are also associated with an abnormal rise in sea level of 30 to 40cm in the western Pacific, causing major flooding on the islands of this region, especially when these abnormally high sea levels are combined with storm surges. The evolution of El Niño events is therefore of particular concern for insular environments.

The rise in the ocean temperature

The increase in the temperature of the surface ocean waters is another problem, which combines with the previous phenomena. A large part of the energy stored by the climate system is stored in the ocean, with the consequence that the first 75m of the ocean have warmed by 0.11°C per decade between 1971 and 2010 (Rhein *et al.*, 2013). Substantial warming is now also clearly measurable at least down to 750m deep (Arndt *et al.*, 2010). The consequences of such changes will be major in the offshore zones: species migrations, including those that are fished, disruption of oxygen exchanges, etc. The consequences should also be significant in coastal areas with strong impacts on coral reefs, which are very sensitive to temperature increases. The gradual increase in surface ocean temperatures, combined with the onset of destructive thermal peaks occurring during El Niño episodes, leads to the concern about an increase in the frequency of bleaching events, and even their persistence (Hoegh-Guldberg, 2011, Gattuso *et al.*, 2014). This could lead to the extinction of many species.

The ocean acidification

Parallel to climate change, pollution from greenhouse gases began generating an increase in the dissolved CO_2 content of ocean water, better known as ocean acidification (Gattuso and Hansson, 2011). Ocean acidification has also been named "the other CO_2 problem" (Turley, 2005, Doney *et al.*, 2009). Indeed, the oceans have absorbed about a third of the anthropogenic CO_2 since the industrial revolution. However, the increase of CO_2 in seawater causes a decrease in pH, *i.e.* making it more acidic. The predictions for the twenty first century involve a decrease in the global mean pH, which may reach 7.8 in 2100 (Ciais *et al.*, 2013) compared to 8.18 before the industrial era and 8.10 at present.

This phenomenon has and will continue to have, a significant impact on the basic chemistry of the ocean, then, through a domino effect, on marine organisms (calcification decrease in many animal skeletonnes or limestone shells) and ecosystems (Pörtner *et al.*, 2014, Gattuso *et al.*, 2014b, Howes *et al.*, in press). Hence specialists argue that the effects of acidification on coral reefs will become very important when the atmospheric CO_2 concentrations exceed 500 ppm (Hoegh-Guldberg *et al.*, 2014).[7]

The future vulnerability of small islands to climate and ocean changes will therefore largely depend upon the evolution of these four pressure factors (sea level, extreme events, global warming and ocean acidification). These island systems are reactive because they are very dependent on environmental conditions. Hence, acidification combined with surface water warming will have even more negative impacts if the coastal ecosystems (reefs, mangroves, etc.) are already subjected to strong anthropogenic pressure, especially if these ecosystems have already undergone significant functional degradation. This also holds for threats due to rising sea levels and the occurrence of more intense tropical cyclones: the more natural coastal systems have been disrupted, sometimes irreversibly, the more their natural ability to adapt will be amputated in the future, and the more the impacts of extreme events and of more gradual changes will be significant. Thus, the lack of sustainability of our current development patterns (degradation of marine and coastal ecosystems, disconnection of the modern society from environmental constraints, development of areas exposed to hazards, etc.)

7 The atmospheric CO_2 concentration threshold of 400ppm was passed in May 2013 at the measuring station of the Mauna Loa observatory (Hawaii). For example, at this same station, the concentration was 386 ppm in 2009.

is at the heart of the threats that climate change poses on coastal areas, and especially islands (Duvat and Magnan, 2014).

IMPACTS ET VULNÉRABILITÉ DES PETITES ÎLES

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

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, supplemented by available knowledge on the responses of island systems to the different types of natural and human pressures, can allow assessing the main impacts that climate change will have. The effects on the evolution of the islands and of their main coastal ecosystems, coral reefs and mangroves, will be successively addressed below.

A reduction in the surface of the islands and a retreat of the coastline

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 of the complexity of their interactions. These factors can be both natural (sediment reservoirs, storm impacts, responses 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, in the coming decades, a decrease in area of the islands can be expected, particularly for coral islands. A country like the Maldives, where the altitude of 80% of the emerged land area is less than 1m high, will indeed most probably undergo a significant reduction in its area under the effect of sea level rise. However this stress factor has, like the other ones (frequency and intensity of storms, deterioration of the health of coral reefs, etc.), varying impacts from one island to the other, depending on the geomorphological and human context.

For example, the islands already affected by erosion or whose coastline is heavily developed will not benefit from any natural mechanism of elevation allowing them 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 coastline where sediment can accumulate. On one hand, nowadays, these two conditions are only met in a limited number of inhabited islands, but on the other hand, such a natural adjustment mechanism could probably only succeed on certain little- or un-developed Islands.

Similarly, on the coastal fringe of higher standing islands, the lowlands will be gradually won by the sea, where no accretion mechanism will be able to generate their elevation or seaward extension, unless technical interventions, such as landfilling, maintain these areas above sea-level.

In some cases, a decrease in the area of low islands will probably lead to question their viability, as their resources will become insufficient to meet the needs of their inhabitants. The coastal plains of the higher islands will also be subjected to climate pressures resulting in impacts on the communities that will be all the more stronger as the demographic pressure is high and as 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 be necessarily predictable.

Coral reefs under threat

Face to climate change effects, the behavior of coral reefs will play a key role in the response of many islands. However, the future of reefs depends on the combination of various factors, the main ones including the rate of sea level rise, the temperature of surface ocean water, the acidification rate of ocean waters, the current vitality of corals and their ability to withstand shocks, and the extent of weakening of their resilience by human activities (Gattuso *et al.*, 2014). The rates of rising sea level predicted for the coming decades can theoretically allow corals to compensate with growth for the increasing level of the ocean, as they can grow 10 to 25mm/year. During the last rise in sea level, the vast majority of reefs have followed the rise step by step (keep-up reefs) or after a time lag (catch-up reefs). However these elements remain theoretical because in reality, the behavior of corals depends on the ecological conditions that prevail in the different parts of the ocean. In areas where the state of the reef is good, the corals will eventually grow with the rise in sea level, but in places where they will tend to degrade significantly, they may come to disappear. Various factors, ranging from global to local, determine the quality of ecological conditions. At the global level, they will deteriorate due to ocean acidification, which as mentioned earlier, leads to a decrease of the calcification rate in calcareous skeleton creatures as well as a simultaneous reduction in the resistance of these organisms to natural and anthropogenic sources of stress.

At both regional and local scales, the main factors influencing the behavior of corals are sea surface temperatures (mean value and intra- and interannual variations), pH, storms and the degree of human disturbance of the environment. As for bleaching coral colonies, the models developed for Tahiti (French Polynesia) over the 1860 to 2100 period show that the surface temperatures remained below the threshold until 1970[8], meaning that no bleaching episode had occurred previously (Hoegh-Guldberg, 1999). Since that date, where the increase in ocean temperatures due to climate change has been evidenced, the ocean temperature has been consistently exceeding this threshold during El Niño events, leading to inevitable bleaching events. Using the predicted changes in ocean temperatures, the models forecast bleaching to take place annually from 2050 onwards, which could undermine the ability of corals to survive. The increasing frequency of these events may not allow enough time for coral reefs to regenerate between two heat peaks, although 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 are less resilient than those that develop 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 different species of corals can differ. A single species does not inevitably react identically to two thermal stresses of the same intensity, as has been observed during a monitoring program carried out in 1996, 1998 and 2002 on coral reefs of the Arabian Gulf (Riegl, 2007). In 1996, the branching corals of the genus Acropora were completely decimated, but regenerated rapidly and were not affected in 2002. This suggests that corals do have a capacity to adapt. Observations carried out in the eastern Pacific lead to the same conclusions. The 1982-1983 El Niño episode appeared to have been more destructive than that of 1997-98, leading to the hypothesis that disasters may contribute to select the most resistant individuals (Glynn *et al.*, 2001). The resilience of coral also depends on their degree of weakening due to diseases, whose development has been promoted by the thermal peaks in certain regions (Caribbean, for example). Finally, resistance and resilience of corals depend largely on the degree of human disturbance. Yet today global estimations show that 30% of coral reefs will be extremely degraded and 60% will be severely threatened by 2030 (Hughes *et al.*, 2003). Anthropogenic pressure on reefs is also likely to increase in island systems due to a generally high population growth.

Why is so much importance given to the development of coral reefs when assessing the fate of small islands? The reason is that the total or partial disappearance of coral reefs would result on the one hand, in the prevention of the vertical adjustment mechanism of these islands and coasts to changing sea level, and on the other hand, in an increase in coastal erosion. Indeed, firstly, the death of the reefs would bring both an end to the upward growth of corals as well as reduce the supply of freshly crushed coral debris; secondly, it would generate an increase in marine energy at the coast, causing wave induced erosion, especially in storm conditions. In

8 Although the maximum temperature tolerated by corals varies from one region to another – it is particularly higher in seas than in oceans – globally, bleaching can occur above 30°C.

this configuration, the factor that will play a crucial role in preserving coral coasts will be the state of inert sediment stocks[9] that may be mobilized by marine processes thus compensating for the reduction in the supply of fresh coral debris. The role of these sands that have accumulated on small scale sea beds should not be neglected, as some islands with a poorly developed reef (narrow or only present on part of the coastline) were formed and continue to grow in response to the shoreward transport of these ancient sands (Cazes-Duvat *et al.*, 2002).

Where ecological conditions are favorable for the development of coral, lifeless coral reef flats, like those of Kiribati and Tuamotu for example which consist of a conglomerate platform, could be colonized by new coral colonies. This is also the case for coasts bordered by a rocky reef exempt of coral life. In this respect, the development of a reef could eventually develop the elevation of the flats thus allowing them to follow the progressive sea level rise. Such a development would be clearly in favor of vertical growth of low islands and associated coastal plains, which would in turn be further supplied with coral debris than they are today. Therefore all the coastlines should not necessarily erode. It should nevertheless be noted that the development of corals would not produce immediate benefits for human communities. The processes of colonization and coral growth are very slow and may even slow down in the future, as ecological conditions tend to deteriorate.
The islands and coasts that won't 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 the mangroves?

Mangroves play an equally important role as coral reefs in preserving low-lying islands and sandy coasts, and in protecting human developments during storms. These coastal forests generally continue to expand in the areas where mangroves have not been cleared and where the mudflat they colonize continue to be supplied with sediments. In many atolls, on the inside of the lagoon, the extension of mangroves 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 should cause an inshore migration as the different ecological zones that make 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 the level of human pressure on the ecosystem. In favourable conditions (active sedimentation and reduced human pressure) the rise in sea level can be compensated by the rising of small scale sea beds. In this case, mangroves remain or continue to expand offshore. The most sensitive areas are undoubtedly those that are already affected by severe erosion, causing the destruction of mangroves, and/or those which have already been degraded by man.

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 assemblage and interactions can show spatial variations, even over short distances. In addition, the present available knowledge on the resilience of corals and mangroves face to natural pressures is still insufficient to establish a definitive diagnosis. While it is undeniable that the reefs will be subjected to increasing pressure in the future, the results from recent studies have brought into perspective the even more pessimistic initial studies. Furthermore as the behaviour of reefs will play a crucial role in the evolution of coral islands and coastal plain sandy coasts, where the morphosedimentary processes are complex and spatially variable, it is not possible to conclude that all coral islands, for example, will be rapidly swept off the face of the planet. In addition to the uncertainties that prevail on many processes, there is also considerable doubt as to the temporality when certain island systems will find themselves under critical situations.

9 Sediments produced by previous generations of coral reefs.

What impact on island resource systems?

To make progress in the chain of impacts of climate change and ocean acidification on human communities, the focus is put on the impact of physical disturbances on land (soil, water, flora and fauna) and marine resources (reef 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). Firstly, the increase in atmospheric temperature leads to increased evapotranspiration[10], causing the soil to dry and an increase in the consumption of brackish shallow groundwater by plants. This groundwater absorption should not be overlooked, as measurements on Tarawa Atoll (Kiribati) have shown that the most common tree, the coconut tree, restored at least 150 liters of water per day to the atmosphere through transpiration. Under these conditions, the expected increase in groundwater pumping by coconut trees and other types of vegetation should significantly strengthen the pressure that is exerted on these reserves that are already used by humans to meet there needs. The degradation of the quality of the soils and the decreasing water resources will further reduce the possibilities of cultivation. Consequently a drop in production should arise, especially for island agriculture, representing a serious challenge regarding food security. An increase in external dependency will follow, especially for rural atolls in many coral archipelagos. Soils will also tend to degrade under the effect of salinization due to rising sea levels and more frequent coastal flooding on the islands and coastal plains that cannot elevate. Moreover, few edible plant species tolerate salt, even though coconut tree can support salt up to a certain threshold beyond which they die. The reduction in exploited areas, especially coconut groves, should reduce the availability of building materials. Also, the gradual evolution of island farming practices towards species that are less resistant to climatic and marine pressures than indigenous species - for example the banana tree being less resistant than the pandanus and the coconut trees - may increase the magnitude 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 (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, which depend on several factors. The most important is the sea level, whose elevation will inevitably reduce the volume of underground freshwater reserves. According to the principle of Ghyben Herzberg that governs the functioning of aquifers, any rise in sea level causes a reduction in volume. More frequent or even systematic coastal flooding during high spring tides, are the source of repeated intrusions of salt water into the groundwater, thus contributing to the deterioration of its quality. The islands and coasts under strong coastal erosion should be more affected by the decrease in the volume and quality of underground lenses. Another important factor is rainfall, which determines the rate and frequency of recharging the underground freshwater lens and rivers that cross the coastal plains. To date, there is no reliable mean of forecasting the evolution of rainfalls. Moreover, there are still uncertainties regarding the freshwater resources of certain high islands. It is thus impossible to identify the islands and archipelagos that will be most affected by the degradation of water resources. A reduction in the volume of available water is to be expected in areas where droughts will be more frequent and/or drawn-out. Consequently, the water will become more salty, causing the increase in the frequency and severity of crop mortality peaks (for coconut and taro, in particular) which are already being observed. The removal of water from the groundwater during a drought has the further effect of reducing its thickness, which means that in periods of water shortage, groundwater, which is crucial for the survival of many islanders, may become unfit for consumption. As rainwater tanks on the islands become empty when the drought lasts, this issue could undermine the habitability of certain low-lying islands. Individual access to water should also decrease as a result of the high population growth characterizing these areas.

10 Evapotranspiration represents the different phenomena related to evaporation and transpiration of plants. These two processes are linked by their transpiration, the plants release water absorbed from the ground into the atmosphere. In this way they contribute to the water cycle.

At sea

As stressed in the last IPCC report (Pörtner *et al.*, 2014, Hoegh-Guldberg *et al.*, 2014), there is currently very little information concerning the impacts of climate change on the distribution of fishery resources. The strong pressures that are already at work on coral reefs in some of the most populated areas should increase everywhere where population growth remains strong. As different factors in these areas contribute to the degradation of reefs, available reef resources per inhabitant will decrease. Moreover these resources play an important role in the daily diet of islanders, including the islands where the need for imported products is high (Nurse *et al.*, 2014). This is even more an issue when considering that the possible changes in ocean currents might reduce the presence of pelagic species in certain ocean regions, thereby preventing the consumption transfer on these species. The fishing industry as a whole is therefore being questioned, from the natural resources to the fishing means (ships, ports, etc.), the latter also being destabilized by rising sea levels, extreme events and other sources of stress (economic crisis for example). On top of this, overfishing leads to severe reduction in fish stocks in coastal waters and lagoons as well as offshore.

Even if island systems will have a differentiated response to the signs of climate change and ocean acidification, and despite the uncertainties that remain, it is clear that environmental constraints, which are already strong, are still going to increase. As a consequence, the already limited island resources are to decrease or to become more random than today. Therefore the viability of certain reef islands and island states themselves might eventually be challenged. However, at present the main threat for the sustainability of these islands is unsustainable development that has, over the past few decades, degraded the resources and reduced their resilience to natural pressures (Duvat and Magnan, 2012, 2014). In other words, the main challenges nowadays in coral islands and coastal plains reside in pollution, land disputes, depletion of natural resources, etc., and not only the effects of climate change and the ocean acidification. This conclusion is not a denial that climate change and acidification have and will have a major impact, but it is rather a justification that existing insular communities are going to have to meet a challenge that is yet unmatched with the disturbances that they are already facing today. With relatively poor flexibility, they will have to deal with the impacts of climate change that will in turn be multiplied by the environmental disturbances of recent decades, the latter having greatly increased the vulnerability of ecosystems. Under these conditions, climate change and acidification will act as accelerators of the impacts of current developments. By reducing the area of the islands in a context of high population growth, climate change will in certain cases, generate land conflicts. Furthermore, by generating a decline in reef resources while the need for food is increasing, climate change and acidification will most likely accelerate the deterioration and death of reefs in some areas. The pressure on water resources will also increase. In total, it can be expected that the concentration of the population will increase in the capital cities that are currently the only areas to benefit from alternative solutions (desalinated water, imported food). This will not be without consequences, notably on food security and human health.

It is now feared that due to the combination of the effects of unsustainable development, climate change and acidification, certain archipelagos will no longer be inhabitable 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 considering the pressures of climate change and ocean acidification in a broader context of anthropogenic pressures. The aim is to show how future threats initially take root in the current issues of "unsustainable development", that is to say, non-viable development, illustrated in particular by the strong deterioration of coastal ecosystems and uncontrolled urbanization. In this case, climate change and ocean acidification play the role in the acceleration of pressure 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). Focus is put on the effects of climate change only, since the effects of ocean acidification are for the moment too complex to determine in the specific case of Kiribati. A brief assessment of the natural constraints and socio-economic changes of the last two centuries can explain what pressures the country is currently facing, and in what manner climate change will amplify them. With the questionable future of these areas and island populations, this demonstrates the major importance of overlapping 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 their geographical and historical complexity. In other words, their vulnerability to future environmental changes not only depends on the evolution of the climate/ocean relationship. This basic reasoning is a fundamental step towards understanding vulnerability in all its dimensions, but also to imagine strategies of adaptation that can be locally relevant, consistent and realistic in their implementation.

Like Tuvalu and the Maldives, Kiribati mainly comprises atolls whose evolution depends on the responses of corals to changes in weather and sea conditions. Its exclusive economic zone (EEZ) is vast (3.5 million km^2) and contrasts with the modesty of its land area (726km^2), which is also fragmented into a large number of islands. On an atoll, the dominant element is the lagoon, enclosed by a ring of reef islands that are generally less than 1km^2 in area. They are also not inhabitable on their entire surface due to the presence of mudflats and mangrove swamps, to the strong instability of their coastlines and to very low altitudes in some parts. Summits mainly culminate around 3 to 4m, so the risk of submersion remains very high. As they are young (between 2000 and 4000 years), made of sand and coral debris and exposed to marine processes, their soils are poor and vegetal resources weakly diversified. Water is scarce, brackish (2-3g salt/L) and very sensitive to climatic fluctuations. Water comes from rainfall that infiltrates to form a shallow groundwater lens (from 1 to 2m) proportional in size to the islands. In the southern atolls of Kiribati, the presence of water becomes uncertain during droughts related to El Niño episodes, which can last up to 2 years.

At a human level, three thousand years of history have shaped a territorial organization based on a dual strategy: to ensure that each family has access to a (low) diversity of land and marine resources, and to rationally manage these resources. The delimitation of the islands into transversal strips connecting the lagoon to the ocean allowed each family to exploit the different environments. The habitation was generally located at a distance of 20 to 60 meters from the lagoon coast, sheltered from swell. In the interior, coconut and pandanus trees (wood, palms and fruit) were grown and in very low areas, taro[11] could be found. Families also used to share the operation of fish traps on the ocean side and fish ponds in the sheltered areas. They additionally used to collect shellfish on the foreshore of the muddy lagoon. Island communities made food and coconut provision in anticipation of harsh weather conditions (Di Piazza, 2001). This system supported an access of the population to a diversified diet and attenuated food crises related to fluctuations in the different resources. Nowadays this ancestral approach is hardly used anymore, especially in the most populated urbanized islands (*e.g.*, the South Tarawa Urban District).

Within less than two centuries, Kiribati has experienced five major transformations:

1. The regrouping of habitations into villages in the rural atolls and into urban areas in Tarawa Atoll.
2. The concentration of political power in the capital of the Tarawa atoll, abandoning the self-management system specific to each atoll.
3. The replacement of a rich and complex traditional law by simplistic written law.
4. The replacement of a subsistence economy by a market econom.
5. the disintegration of the traditional land tenure system.

11 Emblematic tuber of the Pacific civilisations (for consumption and for ceremonies). Each family had a portion of "taro garden".

A population boom in the atoll-capital also characterizes the last decades, mainly due to progress made in the field of health. The strong population growth of Kiribati – from 38,000 in 1963 to over 103,000 in 2010 - representing + 171% - is mainly concentrated in the urban district of South Tarawa. This island is now home to half the country's population on only 2% of the territory, with an average population density of 3125 inhabitants per km2. This situation is the cause for *(i)* a rapid degradation of ecosystems and resources, *(ii)* a loss of identity and cultural connection to the environment, and *(iii)* a high population exposure to sea-related hazards due to the settlement of flood-prone and unstable areas, and *(iv)* a growing dependence towards international aid and food imports.

Finally, all of these transformations, put into the perspectives of the first and second sections (weakening of coral reefs, coastal erosion, marine inundation, scarcity of water resources, etc.), can largely explain the vulnerability of Kiribati to climate change and ocean acidification.

THE KEY MESSAGES TO REMEMBER AND AVENUES TO EXPLORE

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

Firstly, the vulnerability of coastal areas to future environmental change does not only depend on rising sea level and intensification of extreme events. Although this review demonstrates that these two pressure factors are very important, they are often the only ones to be blamed in vulnerability assessments carried out in coastal areas. The analysis based on these factors only is therefore too biased as it does not take into account the consequences of global warming nor ocean acidification which 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 (coral reefs, for example) as well as offshore (phytoplankton, for example).

Secondly, this vulnerability does not only depend on pressures related to nature, such as the occasional hazards as well as the more gradual changes in environmental conditions. Anthropogenic factors will also play a decisive role in the future of the islands and, in a larger sense, of their coasts (Duvat and Magnan, 2014). Knowing that climate change and ocean acidification are genuine threats - it would be irresponsible and dangerous to deny it – the extent of tomorrow's difficulties are closely related to both current unsustainable occupation of land area and exploitation of resources.

Finally, if immediate proactive policies could be triggered for the readjustment of territories, for environmental protection and for the modification of the relationship between human communities and their economies and the marine and coastal resources, a major step forward would be made towards adaptation to climate change and ocean acidification. The identification of anthropogenic pressure factors presently at work finally provides many clues for imagining and starting to implement adjustments to environmental changes (Magnan, 2013). Human responsibilities are powerful levers that must be used to reduce future threats.

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Ocean and Climate Platform

Involving the Ocean in the debate on Climate Change

Launched at UNESCO in June 2014, the Ocean and Climate platform is a multi-stakeholder structure including members of the scientific community, non-profit organizations and business organizations that are all concerned about the ocean. It aims to place the ocean at the heart of international climate change debates, particularly at the *Paris Climate 2015* conference.

The Scientific Committee of the Platform is comprised of world-renowned scientists in the fields of oceanography, biodiversity and ecology of the marine environment, but also from social and economic sciences related to the ocean. The texts included here represent an initial synthesis on the key points of ocean and climate issues. They form an essential scientific basis for all, from citizens to decision makers who are implicated in the negotiations and decisions taken within the United Nations Framework Convention on Climate Change, particularly during the COP 21 in Paris in December 2015.

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