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OCEAN AND CLIMATE
SCIENTIFIC NOTES

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 deteriorating.

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.

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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.

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Foreword

Françoise Gaill

For decades, climate change negotiations did not take the ocean into consideration. The following texts reveals a change in mindset and that this planetary environment has finally been given the importance it deserves in climate issues. This document addresses concerns such as the part the ocean plays for the climate and the impacts of climate change on the ocean.

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.

In fact, 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, nor their sensitivity to climate change.

With increasing seawater temperature, the ocean expands and sea level rises. This phenomenon is amplified 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 over 80 cm. The causes and variability of this phenomenon are questions that are addressed in this booklet which also presents a state of our knowledge on the evolution of oxygen concentration in the ocean.

Humanity will have to face the impacts of climate change on coastal populations, as well as on industrial activities in the Arctic region or on the fishing and aquaculture sectors. Islanders are at the frontline of these global evolutions linked to climate change.

Everything cannot be assessed here, and new documents will progressively complete the set of topics that we believe are relevant, including 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, there is very little knowledge 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 it is 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 and evaluate the consequences on ecosystem services, in order to understand the overall mechanisms and to infer the outcomes for our civilization.

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. In fact, facing climate change, the ocean still acts as a shield upon which the future of our planet greatly depends.

Ocean, Heat Reservoir

Sabrina Speich,
Gilles Reverdin,
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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 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%). As a result, 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 there was very little knowledge about the latter. Nonetheless, 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 for both our planet's mild climate and for 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 a large reservoir, that 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 occur as surface water temperature drops in these regions (surface waters lose buoyancy and thrust into the abyss). The mechanism of this vertical dense water transfer related to an increase of sea-water density (caused by a temperature drop or an increase of salinity) is the starting point for the global ocean thermohaline circulation (derived from the Greek Thermos: 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, the renewal of surface water through ocean circulation, 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 OCEAN TEMPERATURE 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. Sea temperature data were measured 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 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).

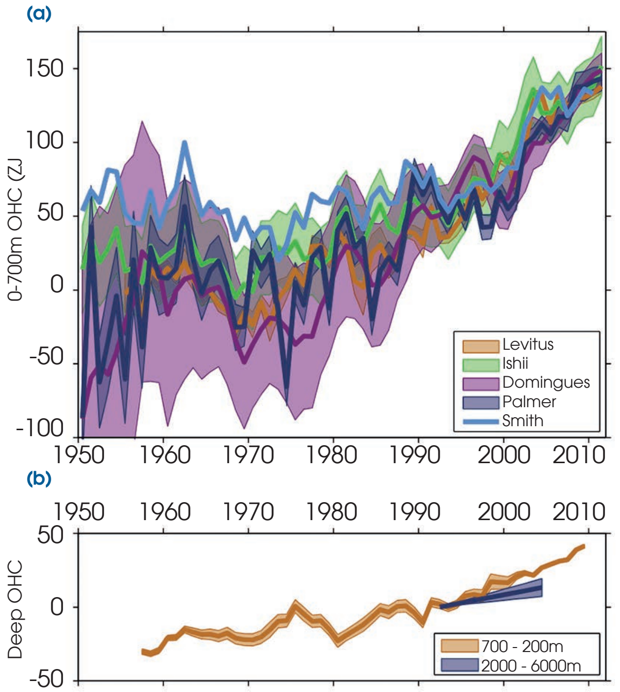

Fig.1— **(a)** Evaluation of the yearly average of the heat content in ZJ (1 ZJ = 10^{21} Joules) calculated from observations in the surface layers of the ocean (between 0 and 700m depth). these estimates have been updated from Levitus *et al.* (2012), Ishii and Kimoto (2009), Domingues *et al.* (2008), 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.

The temperature of the 0-300m layer has increased by about 0.3°C since 1950. This value is approximately half of 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 estimated so far, which may explain, simultaneously with the impact of natural 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

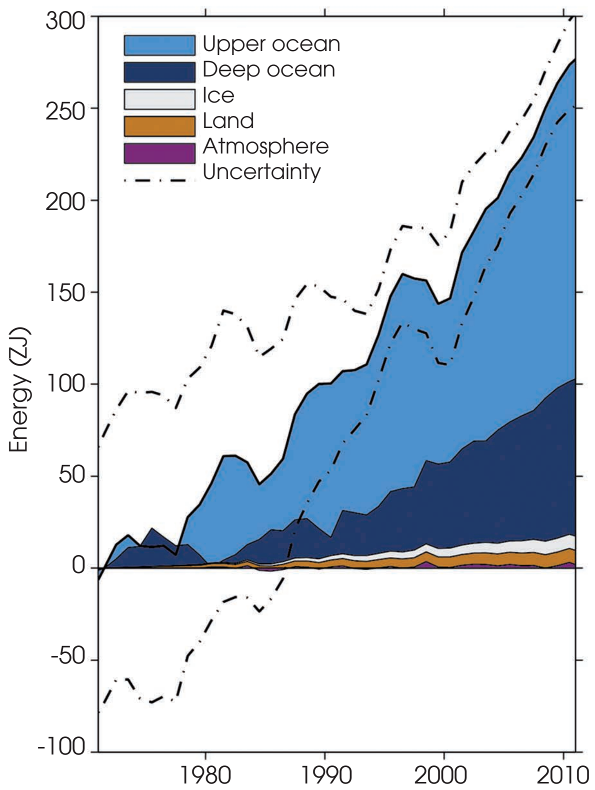

Fig.2— Energy accumulation curve in ZJ with reference to the year 1971 and calculated between 1971 and 2010 for the different components of the global climate system. The sea temperature rise (expressed here as a change in heat content) is significant. The surface layers (light blue, 0 to 700m deep) 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.

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; Rhein *et al.*, 2013). The most notable 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

REFERENCES

- ALLAN R. P., SODEN B. J., JOHN V. O., INGRAM W. and GOOD P., 2010 – *Current Changes in Tropical Precipitation.* Environ. Res. Lett., 5, 025205.
- BALMASEDA M. A., TRENBERTH K. E. and KÄLLÉN E., 2013 – *Distinctive Climate Signals in Reanalysis of Global Ocean Heat Content.* Geophys. Res. Lett. 40, 1754-1759.
- CAZENAVE A., DIENG H., MEYSSIGNAC B., VON SCHUCKMANN K., DECHARME B. and BERTHIER E., 2014 – *The Rate of Sea Level Rise. Nature Climate Change*, vol. 4.
- CUBASH U. *et al.*, 2013 – *Observations : Atmosphere and Surface*, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press.
- DOMINGUES C. M., CHURCH J. A., WHITE N. J., GLECKLER P. J., WIJFFELS S. E., BARKER P. M. and DUNN J. R., 2008 – *Improved Estimates of Upper-Ocean Warming and Multidecadal Sea-Level Rise*. Nature, 453, 1090 – 1093.
- DRIJFHOUT S. S., BLAKER A. T., JOSEY S. A., NURSER A. J. G., SINHA B. and BALMASEDA M. A., 2014 – *Surface Warming Hiatus Caused by Increased Heat Uptake Across Multiple Ocean Basins*. Geophysical Research Letters, 41, (22), 7868-7874.
- DURACK P. J., GLECKLER P. J., LANDERER F. W. and TAYLOR K. E., 2014 – *Quantifying Underestimates of Long-Term Upper-Ocean Warming*. Nature Climate Change.
- DURACK P. J. and WIJFFELS S. E., 2010 – *Fifty-Year Trends in Global Ocean Salinities and their Relationship to Broad-Scale Warming.* J. Clim., 23, 4342 – 4362.
- DURACK P. J., WIJFFELS S. E. and MATEAR R. J., 2012 – *Ocean Salinities Reveal Strong Global Water Cycle Intensification during 1950 to 2000*. Science, 336, 455 – 458.
- HELD I. M. and SODEN B. J., 2006 – *Robust Responses of the Hydrological Cycle to Global Warming.* J. Climate, 19, 5686 – 5699.
- IPCC 5TH ASSESSMENT REPORT, 2013 – *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- ISHII M. and KIMOTO M., 2009 – *Reevaluation of Historical Ocean Heat Content Variations with Time-Varying Xbt and Mbt Depth Bias Corrections.* J. Oceanogr., 65, 287 – 299.
- JACKSON R., STRANEO F. and SUTHERLAND D., 2014 – *Externally Forced Fluctuations in Ocean Temperature a Greenland Glaciers in Non-Summer Months.* Nature Geoscience, 7, 503-508.
- KEELING R. F., KORTZINGER A. and GRUBER N., 2010 – *Ocean Deoxygenation in a Warming World.* Annu. Rev. Mar. Sci., 2, 199 – 229.
- LEVITUS S., ANTONOV J. I., BOYER T. P., LOCARNINI R. A., GARCIA H. E. and MISHONOV A. V., 2009 – *Global Ocean Heat Content 1955 – 2008 in Light of Recently Revealed Instrumentation Problems*. Geophys. Res. Lett., 36, 5.
- PALMER M. D., HAINES K., TETT S. F. B. and ANSELL T. J., 2007 – *Isolating the Signal of Ocean Global Warming.* Geophys. Res. Lett., 34, 6.
- PURKEY S. G. and JOHNSON G. C., 2010 – *Warming of Global Abyssal and Deep Southern Ocean Waters between the 1990S and 2000S : Contributions to Global Heat and Sea Level Rise Budgets*. J. Clim., 23, 6336 – 635.
- RHEIN M. *et al.*, 2013 – *Observations : Ocean.* In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- RIGNOT E., MOUGINOT J., MORLIGHEM M., SEROUSSI H. and SCHEUCHL B., 2014 – *Widespread, Rapid Grounding Line Retreat of Pine Island, Thwaites, Smith, and Kohler Glaciers, West Antarctica, from 1992 To 2011.* Geophys. Res. Lett., 41, 3502 – 3509.
- SCHMIDTKO S., HEYWOOD K. J., THOMPSON A. F. and AOKI S., 2014 – *Multidecadal Warming of Antarctic Waters.* Science, 1227-1231.
- SMITH T. M., ARKIN P. A., REN L. and SHEN S. S. P., 2012 – *Improved Reconstruction of Global Precipitation since 1900.* J. Atmos. Ocean. Technol., 29, 1505 – 1517.
- SYED T. H., FAMIGLIETTI J.S. *et al.*, In Press – *Satellite-Based Global-Ocean Mass Balance Estimates of Interannual Variability and Emerging Trends in Continental Freshwater Discharge.* Proceedings of the National Academy of Sciences.

The Ocean: a Carbon Pump

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The ocean contains 50 times more carbon than the atmosphere and exchanges 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. While this absorption of anthropogenic CO_2 is today the result of physical-chemical processes, marine biology plays a key 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 feedback between climate, the ocean, and its ecosystems require a better understanding in order to predict the co-evolution of atmospheric CO_2 and climate change more reliably as well as to understand the characteristics of a future ocean.

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

The carbon cycle 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 highlights the relative importance of each of these processes as 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 under 0.03% to over 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 slowing 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 (40,000 PgC), 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.

This carbon, represented essentially in the form of bicarbonate ions (HCO_3), is not evenly distributed in the ocean, 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 1). 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 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 1).

Although only a small fraction (~ $0.2 PgCyr^{-1}$) 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

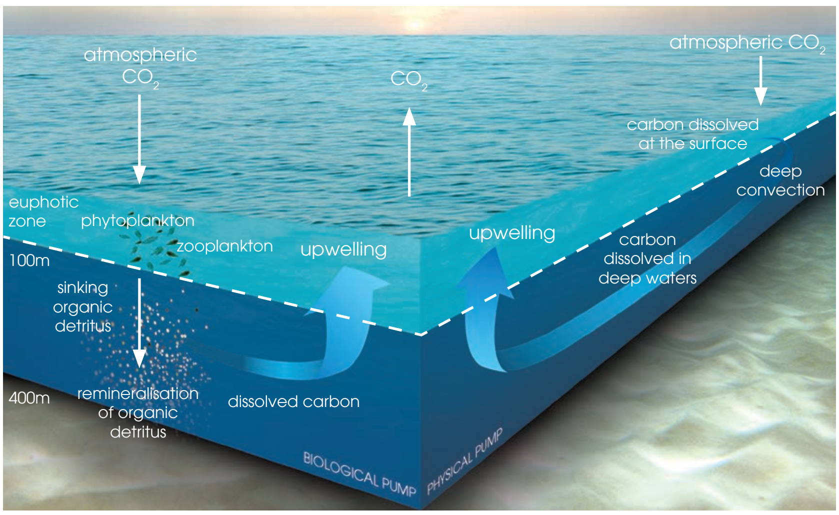

Fig.1— Natural carbon cycle and representation of biological and physical pumps (Bopp *et al.* 2002).

and longer (Denman *et al.*, 2007; Ciais *et 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 the 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. In fact, 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 subsurface 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, 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. Should these changes boost the carbon sink, they could curb climate change and induce negative feedback. On the contrary, in the event of a weakening of the carbon sink, the changes could lead to a positive feedback that could 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 water, 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, though 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 likely 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 is 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.

REFERENCES

- BOPP L., LEGENDRE L. et MONFRAY P., 2002 – *La pompe à carbone va-t-elle se gripper.* La Recherche, 355, 48-50.
- CHARLSON R. J., LOVELOCK J. E., ANDREAE M. O. and WARREN S. G., 1987 – *Oceanic Phytoplankton, Atmospheric Sulphur, Cloud Albedo and Climate.* Nature, 326, 655-661.
- CIAIS P., SABINE C., BALA G., BOPP L., BROVKIN V., CANADELL J., CHHABRA A., DEFRIES R., GALLOWAY J., HEIMANN M., JONES C., LE QUÉRÉ C., MYNENI R. B., PIAO S. and THORNTON P., 2013 – *Carbon and Other Biogeochemical Cycles.* In *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- DENMAN K. L., BRASSEUR G., CHIDTHAISONG A., CIAIS P., COX P. M., DICKINSON R. E., HAUGLUSTAINE D., HEINZE C., HOLLAND E., JACOB D., LOHMANN U., RAMACHANDRAN S., DA SILVA DIAS P. L., WOFSY S. C. and ZHANG X., 2007 – *Couplings Between Changes in the Climate System and Biogeochemistry.* In *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- GONZÁLEZ-TABOADA F. and ANADÓN R., 2012 – *Patterns of Change in Sea Surface Temperature in the North Atlantic During the Last Three Decades : Beyond Mean Trends.* Climatic Change, 115, 419-431.
- LE QUÉRÉ C. *et al.*, 2014 – *Global Carbon Budget.* Earth Syst. Sci. Data Discuss., 7, 521-610.
- PÖRTNER H.-O., D. KARL M., BOYD P. W., CHEUNG W. W. L., LLUCH-COTA S. E., NOJIRI Y., SCHMIDT D. N. and ZAVIALOV P.O., 2014 – *Ocean Systems.* In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A : Global and Sectoral Aspects.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- RHEIN M., RINTOUL S. R., AOKI S., CAMPOS E., CHAMBERS D., FEELY R. A., GULEV S., JOHNSON G. C., JOSEY S. A., KOSTIANOY A., MAURITZEN C., ROEMMICH D., TALLEY L. D. and WANG F., 2013 – *Observations : Ocean.* In *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.

Sea Level Rise

Benoit Meyssignac,
Gilles Reverdin

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).

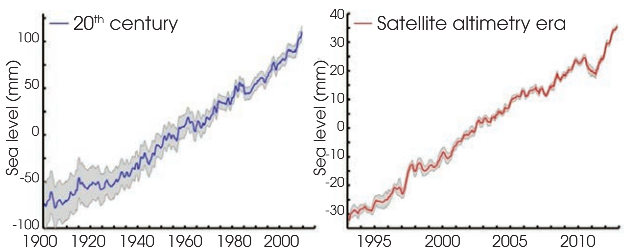

Fig.1— Evolution of the global average sea level, estimated from the reconstruction by Church and White (2011) over the twentieth century (left) and from satellite altimetry over the 1993-2012 period (source: AVISO). The uncertainty associated with each of the curves is in grey. The annual and semi annual 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, scientists have been taking routine measurements of the rising sea levels from space, with 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. Through 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**

Oceanographers have observed that the ocean is getting warmer, by collecting sea temperature measurements 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. 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 explains 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).

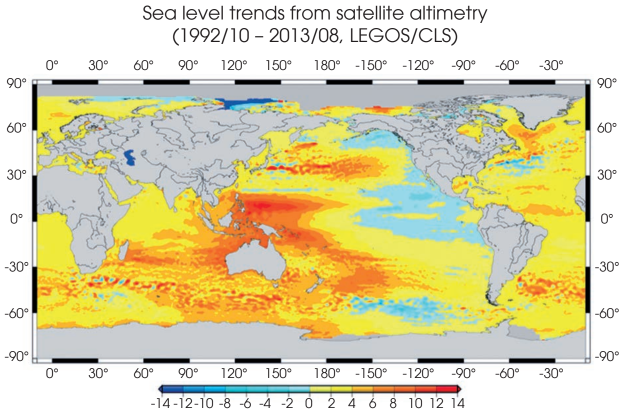

Fig.2— Global map of the geographical distribution of rates of sea level change (1993-2013) according to altimeter measurements from Topex/Poseidon, Jason-1/2, ERS-1/2 and Envisat (source: LEGOS).

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.).

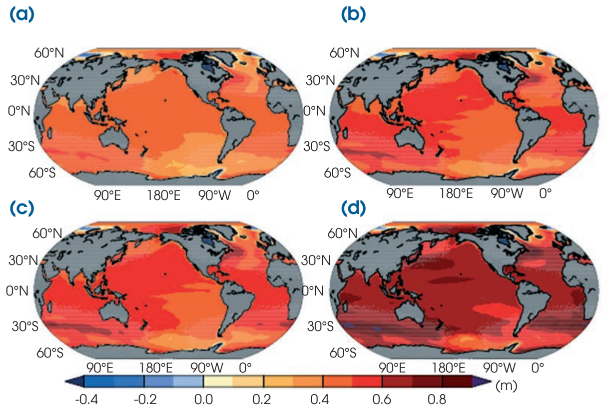

Fig.3— Overall average (21 CMIP5 models) of the change in relative sea level for RCP2.6 scenarios (a), 4.5 (b), 6.0 (c) and 8.5 (d). The impact of thermal expansion of the oceans, the mass of continental ice, continental stocks of liquid water and post-glacial rebound have been taken into account (adapted 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 could 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 should be faster than during the twentieth century. By 2100, the rate of sea level rise could 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 XXIst 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 70 cm 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.

REFERENCES

- ABLAIN M. *et al.*, 2014 – *Improved Sea Level Record over the Satellite Altimetry Era (1993-2010).* From *The Climate Change Initiative Project*. In revision, Ocean Sciences.
- CAZENAVE A. and LE COZANNET G., 2014 – *Sea Level Rise and Coastal Impacts.* Earth's Future, vol. 2, issue 2.
- CAZENAVE A., DIENG H., MEYSSIGNAC B., VON SCHUCKMANN K., DECHARME B. and BERTHIER E., 2014 – *The Rate of Sea Level Rise*. Nature Climate Change, vol. 4.
- CHURCH J. A. and WHITE N. J., 2011 – *Sea-Level Rise from the Late 19th to the Early 21st Century.* Surveys in Geophysics, 32 (4-5), 585-602.
- CHURCH J. A., CLARK P. U., CAZENAVE A., GREGORY J. M., JEVREJEVA S., LEVERMANN A., M. MERRIFIELD A., MILNE G. A., NEREM R. S., NUNN P. D., PAYNE A. J., PFEFFER W. T., STAMMER D. and UNNIKRISHNAN A. S., 2013 – *Sea Level Change.* In *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- IPCC 5th Assessment Report, 2013 – *Climate Change 2013: the Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- MARZEION B., COGLEY J. G., RICHTER K. and PARKES D., 2014 – *Attribution of Global Glacier Mass Loss to Anthropogenic and Natural Causes.* Science, 345 (6199), 919 – 921.
- MEYSSIGNAC B., SALAS Y MELIA D., BECKER M., LLOVEL W. and CAZENAVE A., 2012 – *Tropical Pacific Spatial Trend Patterns in Observed Sea Level : Internal Variability and/or Anthropogenic Signature ?* Climate of the Past, 8 (2), 787-802.
- RIGNOT E., MOUGINOT J., MORLIGHEM M., SEROUSSI H. and SCHEUCHL B., 2014 – *Widespread, Rapid Grounding Line Retreat of Pine Island, Thwaites, Smith, and Kohler Glaciers, West Antarctica, from 1992 To 2011*. Geophys. Res. Lett., 41 (10), 3502 – 3509.
- SHEPHERD A. *et al.*, 2012 – *À Reconciled Estimate of Ice-Sheet Mass Balance.* Science, 338 (6111), 1183 – 1189.
- STAMMER D., CAZENAVE A., PONTE R. M. and TAMISIEA M. E., 2013 – *Causes for Contemporary Regional Sea Level Changes*. Annual Review of Marine Science, vol. 5.
- TIMMERMANN A., MCGREGOR S. and JIN F.-F., 2010 – *Wind Effects on Past and Future Regional Sea Level Trends in the Southern Indo-Pacific*. Journal of Climate, 23 (16).
- YIN J., GRIFFIES S. M. and STOUFFER R. J., 2010 – *Spatial Variability of Sea Level Rise in Twenty-First Century Projections*. Journal of Climate, 23 (17), 4585-4607.

How does the ocean acquire its chemical composition?

Valérie Chavagnac
Catherine Jeandel

Over the geological era, the chemical state of the ocean determines its ability to absorb atmospheric carbon dioxide gas, and therefore to contribute to the Earth climate regulation. Its state depends on the balance between sources and departures of any element delivered to the ocean, both terms extremely difficult and complex to quantify. This article reviews the state of knowledge on dissolved and particulate contributions to the ocean issued from the land-ocean interface (continental flux) on one hand and from the oceanic crust – ocean interface (hydrothermal flux) on the other hand.

GET IN TOUCH WITH THE OCEAN

Over the last 150 years, the concentration of carbon dioxide gas has increased exponentially due to human activities, leading to global warming. At present, the ocean is able to sequester 25% of the annual anthropogenic carbon dioxide flux. Its potential as a sink depends on its chemical state on a global scale. However, the ocean exchanges continuously heat and matter with its surrounding superficial terrestrial envelopes, which are the atmosphere, the polar ice sheets and the continental and oceanic crusts. These exchanges highlight the crucial role played by the ocean in our environment. The characterization and the quantification of these exchanges remain, nevertheless, a major challenge for oceanographers.

Geochemistry may provide important answers on the nature of these exchanges. The chemical composition of the ocean reflects the balance of element budget between 1) inputs – "sources" from continental weathering, atmosphere-ocean interaction, hydrothermal reactions at the oceanic crust – ocean interface and anthropogenic sources, and 2) outputs – "sinks" from secondary mineral precipitation, sediment burial, evaporation and biological and physico-chemical processes acting within the water column (Figure 1). The first global marine geochemical budget proposed in the late 1970's suggested that hydrothermal fluxes were of the same order of magnitude as those issued from the continental sources (Edmonds *et al.*, 1979). Nowadays, the element budget of the ocean is continuously questioned and debated because major progresses have been achieved to observe the natural environment. One of the fundamental missions of oceanographers is to better constrain element fluxes delivered to the ocean and to define their behavior within the marine realm. In other words, it is necessary to fully comprehend global biogeochemical cycles by means of quantifying element fluxes of continental and hydrothermal origin - a step that cannot be ignored to assess response of these cycles to global climate change.

OCEAN MUCH MORE THAN SALTED WATER

Geochemists aim at tracing the transport, dispersal and behavior of each chemical element within the oceanic domain. The ocean is composed of water and salt, which has a relatively homogeneous chemical composition. The salinity of seawater is at about 35 grams per liter of water but may vary from place to place around the globe (10 g/l measured for the Baltic Sea compared to 275 g/l for the Dead Sea). The chemical composition of seawater is dependent upon the mean residence time of each element within the ocean. The oceanic residence time represents the total oceanic inventory of any element divided by its annual flux - whether as sources or sinks - into the ocean. All major elements, which are chemically inert also known as conservative elements, have residence time in the order of millions years - much longer than the 1000 years necessary to mix the entire ocean. In contrast, minor elements whose distribution may be modified by chemical reactions (oxydo-reduction, adsorption, …) and the biological activity, both acting within the oceanic domain, have residence times spanning from several decades up to several thousand years. These trace element species of seawater become important indicators in our understanding of the chemical composition of the ocean, simply because their contrasted and distinctive distributions and behaviors witness the processes acting on their distribution. Therefore, by analyzing modern seawater masses as well as geological materials, which faithfully record the isotopic composition of ocean water, it is possible to assess the variation/evolution of element inputs to the ocean both in time and space. Unfortunately, such approach has strong limitation as it is impossible neither to determine the origin of these fluxes, nor to identify potentials mixing and exchanging processes. This hindrance is overcame by combining chemical element abundances with their respective isotopic systems whether derived from natural radioactive decay (Sr, Nd, Hf, Pb) or stable (O, C, N, Li, Cr, Fe, Mo,…).

To summarize, our understanding of global biogeochemical cycles have made significant steps forward over the last few years by corroborating elemental and isotopic approaches to a number of chemical elements displaying distinctive responses to the natural environmental conditions. Among the most recent discoveries, the continental contribution and hydrothermal fluxes are about to be completely re-assessed (Jeandel and Oelkers, 2015; Resing *et al.*, 2015; Chavagnac, 2015).

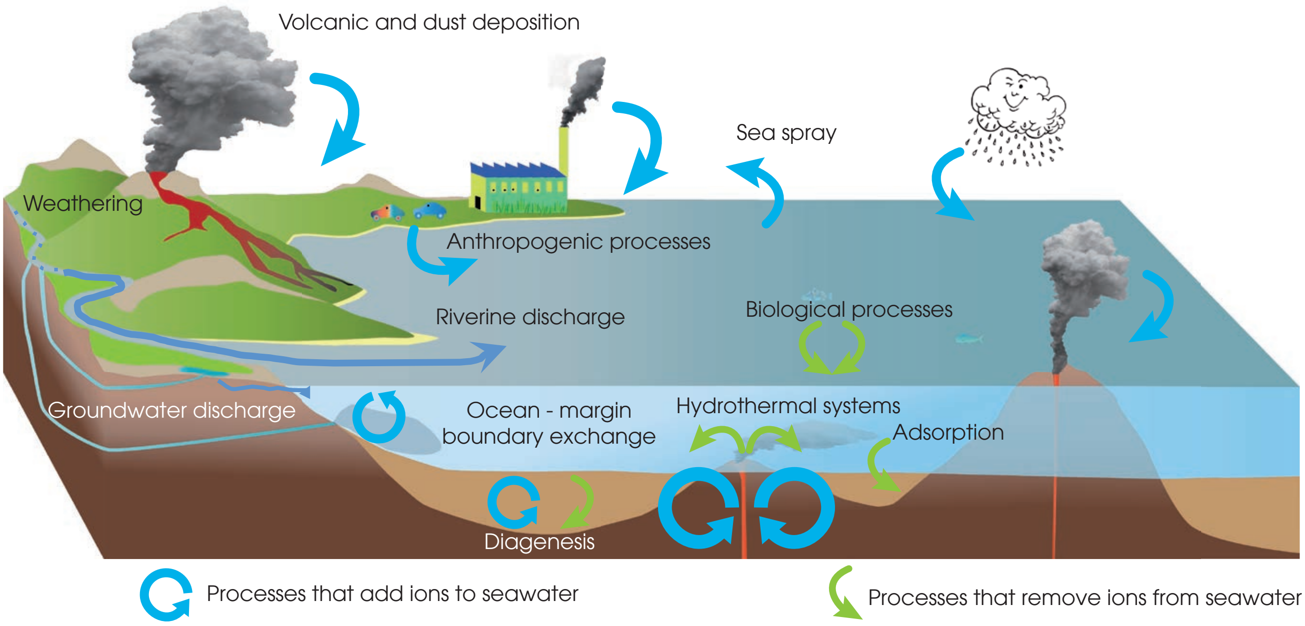

Fig.1 — Major sources and sinks of chemical elements controlling the chemical composition of the ocean.

FLUXES BETWEEN THE CONTINENTS AND THE OCEANS

Young to old emerged continental surfaces are undergoing modern mechanical and chemical alteration processes. The continental-derived erosion products enter the marine realm either as dissolved phase or particulate matter (organic or mineral) and are transported by winds or rivers. Although the preferential sites of continent-ocean interactions take place along coastal areas, winds and oceanic currents enable the oligotrophic ocean to be widely affected. Until recently, the oceanic elemental budget was based solely on two main types of contributions: dissolved phases of rivers and rainwaters together with a fraction of a few percent (according to the element) due to dust dissolution. This fraction may induce an important but local disruption: for example, export of particulate organic carbon in the Equatorial Atlantic Ocean may be increased by 4 folds during dust storm originating from the Sahara, because surface seawaters are suddenly fertilized by iron – a nutrient element provided by this matter (Chavagnac *et al.*, 2007). However, this type of contribution is sporadic both in time and space, compared to continental shelves and oceanic margins, which are major outlets of eroded matter coming from the continent. Indeed, the fluvial flux of suspended particulate matters is 50 times more important than the atmospheric one (Milliman and Farnsworth, 2011). However, once deposited these sediments undergo chemical reactions, which release chemical elements to seawater whereas others are scavenged or trapped. As a result, sediments act both as a sink and a source of elements or chemical compounds for the open ocean. Determining the net fluxes of element contribution to the ocean is a major challenge, even more difficult to assess as the continent – ocean interface is also the one, which conveys the anthropogenic contributions. The most recent studies suggest that the sediments are an important source of chemical elements such as iron - a source, which is overlooked thus far (Jeandel and Oelkers, 2015; Tagliabue *et al.*, 2014). The recent improvements in our understanding of element fluxes between the continent and the ocean will have an immediate effect on biogeochemical models, in particular those describing the global carbon cycle. This illustrates how oceanographic research is still alive and still likely to debate.

HYDROTHERMAL FLUXES

Hydrothermal circulation is due to the penetration and percolation into the oceanic crust and deep-sea sediments of seawater. Along its pathway, numerous chemical reactions take place and alter the surrounding rocks leading to the complete conversion of initial seawater into an acid, reduced and hot hydrothermal fluid (up to 410°C). Thus, some of the seawater major elements such as magnesium are stored in the substratum for secondary mineral formation – it is a Mg sink, whereas metallic trace metals (Fe, Mn, Cu, Zn,…) and alkali metals are enriched by several order of magnitude (up to 10^6) – this is a source. At the seafloor, high temperature hydrothermal fluid mixes with the surrounding deep seawater being neutral, oxygenated and cold, producing the formation of a hydrothermal plume – process giving the nickname of "black smokers" to these systems. A high proportion of hydrothermal dissolved metals fluxes (>90%) precipitate as sulfur, sulfate, poly-metallic and oxy-hydroxide particles, dragging along their way other seawater dissolved trace elements which are absorbed on surface particles (REE, V, P, …). Besides, the hydrothermal iron source can be detected and traced in the seawater column from its emission site at ridge axis over a distance of more than 4300 km (Resing *et al.*, 2015). Consequently, element balance of the ocean is not as simple as that in terms of sinks and sources. All remain to be determined which key factors – organic or mineral – control the behavior of any elements in the marine domain. Hydrothermal systems of high temperature are located at ridge axis and volcanic arcs. The latter are associated with large underwater volcanoes whose summits may be located a few hundred meters below ocean surface, thereby modifying the chemical composition of the upper most portion of seawater.

Alongside these hot fluid circulations, there is the occurrence of cold fluid circulation (<100 °C) within ridge flanks and subducting oceanic plates. Cold hydrothermal fluids exhibit chemical compositions that are drastically different from those of black smokers, as they are basic, enriched in alkali metals but extremely depleted in metallic trace metals. These low-temperature hydrothermal systems are still unknown (geographical extension, temporal variability of chemical fluxes,…) because they do not generate physical and chemical anomalies in the seawater column as do "black smokers", detectable and traceable by modern oceanographic instrumentations available to us at present. To detect the occurrence of low-temperature hydrothermal system at the deep-sea is an extremely difficult task to fulfill. Still, these systems may be of fundamental importance to oceanic element budget and global biogeochemical cycles.

In less than 5 decades of research, there has been the discovery of the first manifestations of hydrothermal activity at the deep sea, to that of a wide inventory of phenomena, both at high and low temperature. It is evident that fluid flow in the oceanic crust and marine sediments is a phenomenon of great diversity and acting on a global scale. However, its implications on the chemical composition of the oceanic crust and the ocean remain poorly understood as evidenced by few constraints of heat and mass transfer. For example, it is estimated that the amount of water flowing off ridge axis is 10 to 100 times greater than that associated with hydrothermal systems at ridge axis (Bickle and Elderfield, 2004; Elderfield and Schultz, 1996). A better quantification of hydrothermal fluxes can only be achieved if the characterization of the geometry and motor (tectonic? thermal? other…) of hydrothermal circulation together with the mechanisms of seawater-rock interactions are fully understood.

REFERENCES

- BICKLE M. and ELDERFIELD H. – *Hydrothermal Fluxes in a Global Context*. In *Hydrogeology of the Oceanic Lithosphere*. Eds DAVIS E. and ELDERFIELD H., Cambridge University Press, 677-690, 2004.
- CHAVAGNAC V. – *When the Crusts Meet the Ocean…* Habilitation à Diriger des Recherches, Université de Toulouse, 201pp, 2015.
- CHAVAGNAC V., WANIEK J.J., ATKIN D., MILTON J.A., LEIPE T., GREEN D.R.H., BAHLO R., HAYES T.E.F. and SCHÜLTZ-BULL D.E. – *Source of Lithogenic Derived Element Fluxes to the Deep Subtropical North East Atlantic Ocean*. Geophysical Research Letters, 34, L21604, doi:10.1029/2007GL030985, 2007.
- EDMOND J.M., MEASURES C., MAGNUM B., GRANT B., SCLATER F.R., COLLIER R., HUDSON A., GORDON L.I. and CORLISS J.B. – *On the Formation of Metal-Rich Deposits at Ridge Crests*. Earth Planetary Science Letter, 46: 19-30, 1979.
- ELDERFIELD H. and SCHULTZ A. – *Mid-Ocean Ridge Hydrothermal Fluxes and the Chemical Composition of the Ocean*. Annual Review of Earth and Planetary Sciences, 24: 191-224, 1996.
- JEANDEL C. and OELKERS E.H. – *The Influence of Terrigenous Particulate Material Dissolution on Ocean Chemistry and Global Element Cycles*. Chemical Geology, 404 : 41-51, 2015.
- MILLIMAN J.D. and FARNSWORTH K.L. – *River Discharge to the Coastal Ocean. A Global Synthesis*. Cambridge University press. 382 pp, 2011.
- RESING J.A., SEDWICK P.N., GERMAN C.R., JENKINS W.J., MOFFETT J.W., SOHST B.M. and TAGLIABUE A. – *Basin-Scale Transport of Hydrothermal Dissolved Metals across the South Pacific Ocean*. Nature, 523(9), doi : 10.1038/nature14577, 2015.
- TAGLIABUE A., WILLIAMS R.G., ROGAN N., ACHTERBERG E.P. and BOYD P.W. – *A Ventilation-Based Framework to Explain the Regeneration-Scavenging Balance of Iron in the Ocean*. Geophysical Research Letters, 41, 7227-7236, 2014.

Ocean Acidification

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Each day, the oceans absorb 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 skeletons, 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 is 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, skeletons 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^+ (protons). It is not practical to refer to the concentration of protons, as the 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 protons (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 skeletons and shells (corals, mussels, oysters etc.). Many of these calcifying plants and animals will thus face difficulties when building these structures, and their skeletons and shells might even dissolve. When seawater acidity reaches a certain threshold it becomes corrosive to limestone, the material used to form shells and skeletons.

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 levels. 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=RnqJMInH5yM 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 Ocean is Out of Breath

Kirsten Isensee,
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Denise Breitburg,
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Véronique Garçon,
Luis Valdés

The decrease in oxygen content (deoxygenation) of coastal and oceanic waters worldwide has worsened in recent decades. The main causes are climate change (warmer water holds less oxygen and causes increased stratification, which reduces ventilation, *i.e.* oxygen replenishment of the ocean interior and estuaries), and measurably higher nutrient concentrations (eutrophication) due to intensified human activities affecting coastal areas. Open-ocean deoxygenation, warming and ocean acidification are all driven by increased atmospheric carbon dioxide (CO_2); they constitute multiple stressors for marine ecosystems, the socio-economic consequences of which are only just beginning to be appreciated.

The problem of decreasing oxygen content (deoxygenation) of coastal and oceanic waters worldwide has worsened in recent decades, primarily as a result of climate change, agricultural runoff and inputs of human waste. Deoxygenation of marine waters is predicted to further worsen with continued increases in global temperatures and human population size, with widespread consequences. Oxygen is a fundamental requirement for all aerobic life, from the intertidal to the greatest depths of the ocean. Oxygen is critical to the health of the planet, playing a direct role in the biogeochemical cycling of carbon, nitrogen, and many other key elements. The scale of deoxygenation ranges from small coastal and estuarine regions to vast areas of the interior open ocean, termed oxygen minimum and limiting zones. The effects of local deoxygenation can be translated to larger scales through the migration of organisms and the ecological, economic and societal consequences of lost fisheries and aquaculture production in affected habitats. Ocean deoxygenation was discussed in the latest IPCC report (2014), but the global nature of this emerging threat to the ocean has not been fully acknowledged or incorporated into planning by policymakers and stakeholders at the global level. Deoxygenation related to agriculture and human waste has generally been managed on a local or regional level, and low oxygen in deeper and upwelled water, historically viewed as a largely natural phenomenon, is only now recognized as a consequence of CO_2-induced climate change.

SCIENTIFIC BACKGROUND

The ocean is a major actor in mediating global oxygen cycling. Photosynthesis by marine algae produces oxygen, providing at least 50% of the oxygen we breathe; at the same time the ocean experiences a continuous loss of oxygen in its water column and sediments through respiration and equilibration of surface waters with the atmosphere. This oxygen loss is exacerbated by anthropogenic nutrient enrichment of coastal waters and by changes to the Earth's climate caused by increasing atmospheric carbon dioxide.

Hypoxic to anoxic and even sulfidic conditions have been reported for various aquatic systems, from lakes, estuaries and coastal areas to offshore regions of the ocean, where oxygen resupply does not compensate for its consumption (IPCC 2014). A threshold value for hypoxia often used for estuaries and shallow coastal waters is 60 µmol kg^{-1} (approximately 1.5 ml l^{-1} or 2 mg l^{-1}) (Gray *et al.* 2002), and areas with oxygen concentrations below this level are commonly referred to as 'dead zones'. However, tolerance to hypoxia varies greatly among marine taxa; some species require oxygen concentrations far higher than 60 µmol kg^{-1} for unimpaired recruitment and growth, while others are adapted for life in low oxygen conditions. In general, mobile fish and crustaceans tend to be the most sensitive (Vaquer-Sunyer & Duarte 2008). Larger animals usually become increasingly scarce as oxygen concentration falls below 60 µmol kg^{-1} and are ultimately lost from the system.

In the coastal ocean, the number of reported dead zones has increased exponentially since the 1960s with more than 479 systems now reporting oxygen concentrations below 60 µmol kg^{-1} during some part of the year (Fig. 1, e.g. Baltic, Black, Kattegat Sea, Gulf of Mexico, East China Sea) (Diaz & Rosenberg 2008)[1]. Some of the increase can be attributed to improved observation and monitoring strategies, as well as increased awareness of the problem, but much is the result of accelerated and inefficient use of chemical fertilizers, and pollution due to increasing human populations. In estuarine, shelf and upper slope areas, where the bottom is populated by ecologically and economically valuable benthic species, the occurrence of hypoxic/anoxic conditions can cause catastrophic biological losses. Some of the most severe examples of hypoxia in estuaries occurred historically and still occur in systems where raw sewage from large population centres is released directly into waterways. This also represents an important confluence of concerns over human and environmental health that extends beyond food-security concerns related to the potential effects of hypoxia on fisheries and aquaculture.

Fig. 1 — World hypoxic and eutrophic coastal areas (Diaz, unpublished; updated 2015 Diaz & Rosenberg 2008).

In the open ocean, eastern boundary upwelling systems (EBUSs) are characterized by high primary and export production that, in combination with weak ventilation, cause natural oxygen depletion and the development of midwater oxygen minimum zones (Fig. 2, OMZs). These are, defined as areas where subthermocline dissolved oxygen levels are < 20 µmol kg^{-1} (< 0.5 ml l^{-1}), although many species experience limitation at higher oxygen values (Gilly *et al.* 2013). For example, large billfish experience oxygen shortage at < 150 µmol kg^{-1} (3.5 ml l^{-1}; Prince & Goodyear 2006). OMZs play critical roles in atmospheric chemistry and climate through emission of active trace gases (Law *et al.*, 2013) and they affect nearly all aspects of ecosystem structure and function in the water and on the sea floor (Levin 2003; Levin *et al.* 2009). OMZs are highly dynamic over glacial-interglacial periods (Moffitt *et al.* 2015), but they appear to be expanding in tropical and subtropical regions and the NE Pacific as a result of climate change (Stramma *et al.* 2010).

Ocean warming contributes to deoxygenation in several ways: warmer water holds less oxygen and causes increased stratification, which reduces ventilation (oxygen replenishment) of both the ocean interior (Keeling *et al.* 2010, Stramma *et al.* 2008a, 2008b, 2010) and estuaries (Altieri and Gedan 2014). Atmospheric warming creates land-sea temperature differentials that can intensify upwelling of low oxygen waters (Bakun 1990).

Similarly, the latest research results suggest that the potential expansion of coastal hypoxia and OMZs could have large effects on, e.g., fisheries

1 World Resources Institute: Interactive Map of Eutrophication & Hypoxia. www.wri.org/media/maps/eutrophication/

species through habitat compression, altered food webs, and modified species interactions, including with fishermen. Even at non-lethal levels, exposure to low dissolved oxygen concentrations can result in reduced growth and reproduction, as well as altered behaviours and distributions of marine species. This means that ocean deoxygenation will increasingly stress aquatic ecosystems nearshore and in deeper oceanic habitats. The expansion of hypoxic and anoxic zones will affect the biogeochemical and ecological status and functioning of marine and freshwater ecosystems, as well as the delivery of ecosystem services. As the ocean is locally out of breath, the global ecosystem service of providing an environment conducive to life is hampered. Model simulations still have difficulties in properly representing oxygen historical data of the last 40 years (Cabré *et al.*, 2015). Clearly we lack a full understanding of the mechanisms controlling oxygen in the ocean interior and on the shelves. Nevertheless, climate model projections predict continued and intensified ocean deoxygenation into the future (e.g. Matear *et al.* 2000; Bopp *et al.* 2002, 2013; Oschlies *et al.* 2008). Hindcasting of these models is supported by the geological record, which illustrates expansive ocean anoxic events that follow climate excursions and glacial interglacial periods (Moffitt *et al.* 2015).

STRATEGIES FOR THE FUTURE

Deoxygenation, along with ocean warming and ocean acidification form a deadly trio of threats to ocean life. These pressures are of critical importance to marine ecosystems because they are accelerating drastically in a short timeframe (Gruber 2011; Mora *et al.* 2013; Bopp *et al.* 2013). Future scenarios for oxygen in the coastal areas and the open ocean will largely depend on a combination of drivers related to global environmental change and land-use, including warming, a growing human population, especially along the coasts, and agricultural practices. Under a business as-usual-scenario, the amount of reactive nitrogen entering the ocean is projected to grow by 50% by 2050 (Noone *et al.* 2012), leading to the increased frequency, intensity and duration of coastal hypoxia. At the same time intensifying upwelling winds (Sydeman *et al.* 2014, Wang *et al.* 2015) and altered circulation (Bograd *et al.* 2008, 2014) are bringing OMZ waters closer to shore and onto the shelf where they can interact with watershed and coastal sources of hypoxia (Feely *et al.* 2008, 2010). Integrated action is urgently required to prevent and remediate hypoxia (Levin & Breitburg 2015).

Much of the information we have about hypoxia is based on scientific activities from researchers in North America, Europe and Asia, but recent findings also indicate that the Peru-Chile margins, West Africa and the Northern Indian Ocean and Bay of Bengal are increasingly vulnerable to deoxygenation events on the shelf (Hofmann *et al.* 2011). Examples illustrating severe hypoxia as a result of this human-induced threat can be found in the past, e.g. the estuary of the Thames River in the UK and the Delaware River in the US. This is a serious problem in developing and rapidly industrializing countries, e.g. the Pearl River estuary in China. We know very little about oceanographic conditions in the least populated parts of the planet – in the open ocean and oceanic islands, however it is clear that some of these systems are affected as well. A global network would facilitate and improve capabilities for ocean oxygen monitoring and help identify the knowledge gaps in order to direct further research. New collaborative research is needed to expand global coverage of oxygen data, to revise model calculations and standardize applied methods, to improve predictions related to food security and tourism, and to evaluate impacts on non-market ecosystem services such as carbon sequestration, nutrient cycling, biodiversity, and

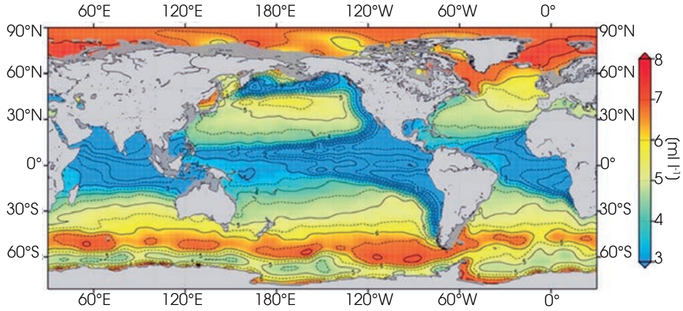

Fig.2 — Annual average oxygen concentration ml l^{-1} at 200 m depth (one-degree grid, contour interval 0.5 ml l^{-1}) (World Ocean Atlas 2013, Garcia *et al.* 2014).

food web support. The global extent and threat to human health and marine ecosystem services of ocean deoxygenation are just beginning to be appreciated; the social and economic consequences have yet to be determined but are likely to be significant. Thus, one of the biggest challenges for future scientific actions is to value the impact of ocean deoxygenation. To date, needed monetary assessments taking the market and non-market consequences of decreased oxygen concentration into account are still very scarce, too general (Mora *et al.* 2013), or are restricted to certain areas in the world, e.g. the Gulf of Mexico (Rabotyagov *et al.* 2014).

The good news is that when the cause of hypoxia is eutrophication; it is possible to recover oxygen levels even in the deadest dead zones. However, marine sediments introduce a delay in the recovery but due to the non-linearity of marine processes , that is difficult to assess and may vary across systems. Moreover, warming will impede the recovery of hypoxic areas, and may require greater reductions in nutrient release to waterways (Capet *et al.*, 2013). Both treatments of human waste and dramatic increases in fertilizer-use efficiency are needed. Institutional capacities for managing waste and nutrients need to be strengthened and installed at the local, national, regional and global levels. New public-private partnerships are also needed across key sectors to stimulate innovation in nutrient reduction and reuse technology. The toolkit for mitigation and adaptation to deoxygenation must be diverse and may include a suite of practices that create a safe space for ecosystems (Scheffer *et al.* 2015). Among these are water quality management, reduced harvesting or fishery closures during low oxygen seasons, creation of oxygenated refugia or marine protected areas, restoration of circulation or flushing regimes in enclosed water bodies, and control of stress from disease, contaminants, habitat degradation or invasive species. Open-ocean deoxygenation, warming and ocean acidification are all driven by increased atmospheric CO_2. Therefore, the most effective solution to mitigate global environmental change is curbing carbon emissions. It is critical to recognize and understand these climate stressors as cumulative impacts interacting with other human activities, and to manage ocean ecosystems accordingly.

The Ocean's multiple stressor challenge
Elevated temperatures, higher acidity, decreased oxygen

All regions of the ocean are impacted by multiple stressors. The biological response to these is assumed to exhibit a strong variation and complexity. The reduction in local stressors can potentially affect the impact of global drivers. Restricting fisheries can sometimes compensate for mortality and lost production due to hypoxia (Breitburg et al. 2009), but has consequences to human food supplies and economies. In order to manage our ocean sustainably the impact of multiple stressors has to be considered while calculating and predicting our future marine environment.

While the chemical and physical changes associated with ocean warming, acidification and deoxygenation occur all over the world, the imprint of these global stressors will have a strong regional and local nature. The coalescence of the different global stressors in certain regions is already creating a number of 'hotspots', e.g. the Eastern Boundary Upwelling Regions. In addition to these regional 'hotspots', certain marine ecosystems are highly vulnerable to multiple stressors, e.g. coral reefs. Other examples show that top predators in the marine food web of the Eastern Tropical Pacific, also important for the economic development of certain regions, are impaired by deoxygenation, ocean acidification and temperature increase.

The different levels of response require an assessment, including observations, experiments and forecast models, taking into account the impacts of multiple stressors at the physiological/biogeochemical, the organism, and the ecosystem level.

Following the science, policy has to act to manage the marine resources in light of multiple stressors. Cross-scale governance systems for marine resources need to be developed or implemented. A change of societal behavior should result in reducing local threats, while at the same time a precautionary approach to multiple stressors should be adopted at the global scale. Finally, capacity building is needed in order to transfer the knowledge on data collection, data management and modeling to regions affected by deoxygenation and acidification but where the knowledge and understanding of these processes are still very limited.

REFERENCES

- ALTIERI, A.H. and GEDAN, K.B., 2014 – *Climate Change and Dead Zones.* Global change biology, doi: 10.1111/gcb.12754.
- BAKUN, A., 1990 – *Global Climate Change and Intensification of Coastal Ocean Upwelling.* Science, 247: 198-201.
- BOGRAD, S.J., CASTRO, C.G., DI LORENZO, E., PALACIOS, D.M., BAILEY, H., GILLY, W. and CHAVEZ, F.P., 2008 – *Oxygen Declines and the Shoaling of the Hypoxic Boundary in the California Current.* Geophys. Res. Lett., 35, L12607.
- BOGRAD, S.J., BUIL, M.P., DI LORENZO, E., CASTRO, C.G., SCHROEDER, I.D., GOERICKE, R., ANDERSON, C.R., BENITEZ-NELSON, C. and WHITNEY, F.A., 2015 – *Changes in Source Waters to the Southern California Bight.* Deep-Sea Res. Pt II, 112, 42-52.
- BOPP, L., LE QUERE, C., HEIMANN, M., MANNING, A.C. and MONFRAY, P., 2002 – *Climate Induced Oceanic Oxygen Fluxes: Implications for the Contemporary Carbon Budget.* Global Biogeochem. Cycles 16, doi: 10.1029/2001GB001445.
- BOPP, L., RESPLANDY, L., ORR, J.C., DONEY, S.C., DUNNE, J.P., GEHLEN, M., HALLORA, P., HEINZE, C., ILYINA, T, SÉFÉRIAN, R., TJIPUTRA, J. and VICHI, M., 2013 – *Multiple Stressors of Ocean Ecosystems in The 21St Century: Projections with Cmip5 Models.* Biogeosciences, 10, 6225-6245.
- BREITBURG, D.L., CRAIG, J.K., FULFORD, R.S., ROSE, K.A., BOYNTON, W.R., BRADY, D.C., CIOTTI, B.J., DIAZ, R.J., FRIEDLAND, K.D., HAGY, J.D., HART, D.R., HINES, A.H., HOUDE, E.D., KOLESAR, S.E., NIXON, S.W., RICE, J.A., SECOR, D.H. and TARGETT, T.E., 2009 – *Nutrient Enrichment And Fisheries Exploitation: Interactive Effects On Estuarine Living Resources And Their Management.* Hydrobiologia, 629 (1), 31-47.
- CABRÉ, A., MARINOV, I., BERNARDELLO, R. and BIANCHI, D., 2015 – *Oxygen Minimum Zones in the Tropical Pacific across Cmip5 Models: Mean State Differences and Climate Change Trends.* Biogeosci. Discuss. Special Issue on Low Oxygen Environments.
- CAPET, A., BECKERS, JM, BARTH A., GREGOIRE M., 2013 – *Drivers, Mechanisms and Long-Term Variability of Seasonal Hypoxia on the Black Sea Northwestern Shelf – Is there any Recovery after Eutrophication?* Biogeosciences, 10, 3943-3962.
- DIAZ, R.J. and Rosenberg, R., 2008 – *Spreading Dead Zones and Consequences for Marine Ecosystems.* Science, 321 (5891), 926-929.
- FEELY, R.A., SABINE, C.L., HERNANDEZ-AYON, J.M., IANSON, D. and HALES, B., 2008 – *Evidence For Upwelling Of Corrosive" Acidified" Water Onto The Continental Shelf.* Science, 320 (5882), 1490-1492.
- FEELY, R.A., ALIN, S.R., NEWTON, J., SABINE, C.L., WARNER, M., DEVOL, A., KREMBS, C. and MALOY, C., 2010. *The Combined Effects of Ocean Acidification, Mixing, and Respiration on Ph and Carbonate Saturation in an Urbanized Estuary.* Estuar. Coast. Shelf Sci., 88 (4), 442-449.
- GARCIA, H.E., LOCARNINI, R.A., BOYER, T.P., ANTONOV, J.I., BARANOVA, O.K., ZWENG, M.M., REAGAN, J.R. and JOHNSON, D.R., 2014 – *World Ocean Atlas 2013, Volume 3: Dissolved Oxygen, Apparent Oxygen Utilization, and Oxygen Saturation.* S. LEVITUS, Ed., A. Mishonov Technical Ed.; NOAA Atlas NESDIS 75, 27 pp.
- GILLY, W.F., BEMAN, J.M., LITVIN, S.Y. and ROBISON, B. H., 2013 – *Oceanographic and Biological Effects of Shoaling of the Oxygen Minimum Zone.* Ann. Rev. Mar. Sci., 5, 393-420.
- HOFMANN, A.F., PELTZER, E.T., WALZ, P.M. and BREWER, P.G., 2011 – *Hypoxia by Degrees: Establishing Definitions for a Changing Ocean.* Deep-Sea Res. Pt I, 58 (12), 1212-1226.
- IPCC - FIELD, C.B., BARROS, V.R., MACH, K. and MASTRANDREA, M., 2014 – *Climate Change 2014: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
- GRAY, J.S., WU, R.S.S. and OR, Y.Y., 2002 – *Effects of Hypoxia and Organic Enrichment on the Coastal Marine Environment.* Mar. Ecol.-Prog. Ser., 238, 249 – 79.
- Gruber, N., 2011 – *Warming Up, Turning Sour, Losing Breath: Ocean Biogeochemistry under Global Change.* Philos. T. Roy. Soc., 369, 1980-1996.
- KEELING, R.F., KÖRTZINGER, A. and GRUBER, N., 2010 – *Ocean Deoxygenation in a Warming World.* Annu. Rev. Mar. Sci., 2, 199 – 229.

- LAW, C.S., BRÉVIERE, E., DE LEEUW, G., GARÇON, V., GUIEU, C., KIEBER, D.J., KONTRADOWITZ, S., PAULMIER, A., QUINN, P.K., SALTZMAN, E.S. STEFELS, J., VON GLASOW, R., 2013 – *Evolving Research Directions in Surface Ocean – Lower Atmosphere (Solas) Science.* Environ. Chem, 10, 1-16. http://dx.doi.org/10.1071/EN12159.
- LEVIN, L.A., 2003 – *Oxygen Minimum Zone Benthos : Adaptation and Community Response to Hypoxia.* Oceanogr. Mar. Biol. 41, 1-45.
- LEVIN, L.A. and BREITBURG, D.L., 2015 – *Linking Coasts and Seas to Address Ocean Deoxygenation.* Nat. Clim. Chang. 5.
- LEVIN, L.A. EKAU, W., GOODAY, A., JORRISEN, F., MIDDELBURG, J., NEIRA, C., RABALAIS, N., NAQVI, S.W.A. and ZHANG. J., 2009 – *Effects Of Natural And Human-Induced Hypoxia On Coastal Benthos.* Biogeosciences 6, 2063-2098.
- MATEAR, R.J., HIRST, A.C., MCNEIL, B.I., 2000 – *Changes in Dissolved Oxygen in the Southern Ocean With Climate Change.* Geochem. Geophys. Geosyst., 1 2000GC000086.
- MOFFITT, S.E., MOFFITT, R.A., SAUTHOFF, W., DAVIS, C. V., HEWETT, K. and HILL, T.M., 2015 – *Paleoceanographic Insights on Recent Oxygen Minimum Zone Expansion : Lessons for Modern Oceanography.* PloS one, 1, 39.
- MORA, C., WEI, C.-L., ROLLO, A., AMARO, T., BACO, A.R., BILLETT, D., BOPP, L., CHEN, Q., COLLIER, M., DANOVARO, R., GOODAY, A.J., GRUPE, B.M., HALLORAN, P.R., INGELS, J., JONES, D.O.B., LEVIN, L.A., NAKANO, H., NORLING, K., RAMIREZ-LLODRA, E., REX, M., RUHL, H.A., SMITH, C.R., SWEETMAN, A.K., THURBER, A.R., TJIPUTRA, J.F., USSEGLIO, P., WATLING, L., WU, T. and YASUHURA, M., 2013 – *Biotic and Human Vulnerability to Projected Changes in Ocean Biogeochemistry over The 21St Century.* PLoS Biology, 11 (10) : e1001682. doi : 10.1371/journal.pbio.1001682.
- NOONE, K., SUMAILA, R. and DÍAZ, R.J., 2012 – *Valuing the Ocean Draft Executive Summary.* Stockholm Environmental Institute.
- OSCHLIES, A., SCHULTZ, K.G., RIEBESELL, U. and SCHMITTNER, A., 2008 – *Simulated 21 Century's Increase in Oceanic Suboxiain Co_2-Enhanced Biotic Carbon Export.* Global Biogeochem. Cycles, 22, GB4008, doi : 10.1029/2007GB003147.
- PRINCE, E.D. and GOODYEAR, C.P., 2006 – *Hypoxia-Based Habitat Compression of Tropical Pelagic Fishes.* Fish. Oceanogr., 15, 451-464.
- RABOTYAGOV, S.S., KLING, C.L., GASSMAN, P.W., RABALAIS, N.N. and TURNER, R.E., 2014 – *The Economics of Dead Zones : Causes, Impacts, Policy Challenges, and a Model of the Gulf of Mexico Hypoxic Zone.* Rev.. Environ. Econ. Pol., 8 (1), 58-79.
- STRAMMA, L., BRANDT, P., SCHAFSTALL, J., SCHOTT, F., FISCHER, J. and KÖRTZINGER, A., 2008 – *Oxygen Minimum Zone in the North Atlantic South and East of the Cape Verde Islands.* J. Geophys. Res., 113, doi : 10.1029/2007JC004369.
- STRAMMA, L.,JOHNSON, G.C., SPRINTALL, J. and MOHRHOLZ, V., 2008 – *Expanding Oxygen-Minimum Zones in the Tropical Oceans.* Science, 320, 655 – 658.
- STRAMMA, L., SCHMIDTKO, S., LEVIN, L.A. and JOHNSON, G.C., 2010 – *Ocean Oxygen Minima Expansions and their Biological Impacts.* Deep-Sea Res. Pt. I, 57 (4), 587-595.
- SCHEFFER, M., BARRETT, S., CARPENTER, S.R., FOLKE, C., GREEN, A.J., HOLMGREN, M., HUGHES, T.P., KOSTEN, S., VAN DE LEEMPUT, I.A., NEPSTAD, D.C., VAN NES, E.H., PEETERS, E.T.H.M. and WALKER, B., 2015 – *Creating a Safe Space for Iconic Ecosystems.* Science, 347, 1317-1319.
- SYDEMAN, W.J., GARCÍA-REYES, M., SCHOEMAN, D.S., RYKACZEWSKI, R.R., THOMPSON, S.A., BLACK, B.A., BOGRAD and S.J., 2014 – *Climate Change and Wind Intensification in Coastal Upwelling Ecosystems.* Science, 345 (6192), 77-80.
- VAQUER-SUNYER, R. and DUARTE, C. M., 2008 – *Thresholds of Hypoxia for Marine Biodiversity.* Proc. Natl. Acad. Sci., 105, 15452 – 15457.
- WANG, D., GOUHIER, T, MENGE, B. and GANGULY A., 2015 – *Instensification and Spatial Homogenization of Coastl Upwelling under Climate Change.* Nature, 518, 390-394.
- WORLD RESOURCES INSTITUTE – www.wri.org/our-work/project/eutrophication-and-hypoxia/interactive-map-eutrophication-hypoxia.

The Deep Ocean: Which Climate Issues?

Nadine Le Bris

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 reflect 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 millennia 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, special places of biodiversity and productivity, and their functioning and associated "services" could be particularly vulnerable to climate 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 function as refuge and nursery 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, conversely accelerate transfers of material from the continental shelf or even from continents to the deep waters.

To this must be added the 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 skeletons 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, where 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 additionnally 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).

REFERENCES

- ADAMS D. K., MCGILLICUDDY D. J., ZAMUDIO L., THURNHERR A. M., LIANG X., ROUXEL O., GERMAN C. R. and MULLINEAUX L. S., 2011 – *Surface-Generated Mesoscale Eddies Transport Deep-Sea Products from Hydrothermal Vents*. Science 332, 580 – 583.
- BOETIUS A., ALBRECHT S., BAKKER K., BIENHOLD C., FELDEN J., FERNANDEZ-MENDEZ M., HENDRICKS S., KATLEIN C., LALANDE C., KRUMPEN T., NICOLAUS M., PEEKEN I., RABE B., ROGACHEVA A., RYBAKOVA E., SOMAVILLA R. and WENZHOFER F., 2013 – *RV Polarstern ARK27-3-Shipboard Science Party. Export of Algal Biomass from the Melting Arctic Sea Ice.* Science 339, 1430–1432.
- DE LEO F. C., SMITH C. R., ROWDEN A. A., BOWDEN D. A. and CLARK M. R., 2010 – S*ubmarine Canyons : Hotspots of Benthic Biomass and Productivity in the Deep Sea*. Proc. R. Soc. B Biol. Sci. 277, 2783 – 2792.
- GLOVER A. G. *et al.*, 2010 – *Temporal Change in Deep-Sea Benthic Ecosystems: a Review of the Evidence from Recent Time-Series Studies.* Advances in Marine Biology. vol. 58, pp. 1-79.
- GUINOTTE J.-M., ORR J., CAIRNS S., FREIWALD A., MORGAN L. and GEORGE R., 2006 – *Will Human-Induced Changes in Seawater Chemistry Alter the Distribution of Deep-Sea Scleractinian Corals ?* Frontier in Env. and Ecol., 4 (3) : 141 – 146.
- LEVIN L. A. and SIBUET M., 2012 – *Understanding Continental Margin Biodiversity : a New Imperative.* Annu. Rev. Mar. Sci. 4, 79 – 112.
- MORA C. *et al.*, 2013 – *Biotic and Human Vulnerability to Projected Changes in Ocean Biogeochemistry over the 21st Century.* PLoS Biol. 11, e1001682.
- RAMIREZ-LLODRA E. *et al.*, 2010 – *Deep, diverse and definitely different : unique attributes of the world's largest ecosystem.* Biogeosciences 7, 2851 – 2899.
- RODER C., BERUMEN M. L., BOUWMEESTER J., PAPATHANASSIOU E., AL-SUWAILEM A. and VOOLSTRA C. R., 2013 – *First Biological Measurements of Deep-Sea Corals from The Red Sea.* Sci. Rep. 3.
- SOLTWEDEL T. *et al.*, 2005 – *Hausgarten : Multidisciplinary Investigation at a Deep-Sea Long-Term Observatory.* Oceanography 18 (3). 46-61.
- STRAMMA L., SCHMIDTKO S., LEVIN L. A. and JOHNSON G. C., 2010 – *Ocean Oxygen Minima Expansions and their Biological Impacts.* Deep Sea Res. Part Oceanogr. Res. Pap. 57, 587 – 595.

The Southern Ocean

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The southern part of the global ocean is furthest away from any industrial or human activity. Yet since several decades, many observers have reported significant changes within the ecosystems as well their indigenous species. In most cases, these disturbances have been connected to the consequences of human activities, whether indirect (increased temperature, changes in seasonal sea ice, consequences of the hole in the ozone layer, acidification) or direct (fisheries exploitation of living resources). The magnitude of these pressures varies across the different regions of the Southern Ocean. Although the image of an undiversified ocean is generally etched in the collective mind, the biogeographic atlas of the Southern Ocean (De Broyer *et al.*, 2014) in which over 9064 species have been identified, shows that this is certainly not the case. Disturbances that are now being observed are presumed to modify the functioning of these ecosystems and trophic webs. This also concerns the modification of habitats of pelagic and benthic species, from primary producers to top predators, from coastal to deep-water species, from the sub-Antarctic ice-free areas to sea ice-covered zones. A well-known example is the modification of the sea ice regime around the Antarctic Peninsula although changes have been observed at variable degrees of intensity all around the continent. This ice is nonetheless necessary for the completion of the life cycle of many species, such as Antarctic krill whose exceptional biomass is at the basis of the diet of many predators including birds or marine mammals. Icebergs or the recent dislocation of large ice shelves are also known to have a major impact on benthic communities. Finally, the sub-Antarctic areas, at the northern boundary of the Southern Ocean might be the most affected by climate change. In this context, it is important to estimate how the biodiversity of this ocean, which has been accustomed to extreme conditions for almost 34 million years, will be able to adapt to these new conditions.

INTRODUCTION

The Southern Ocean is the last ocean to have been explored. Located in the southern hemisphere, it is the only ocean which is not surrounded by continents (figure 1). The Antarctic continent at the South Pole is a land of science that is internationally managed by the Antarctic Treaty. This ocean therefore has an opposite configuration to the other Polar Ocean, the Arctic Ocean, which is surrounded by the American and Eurasian continents with the neighbouring countries exercising their sovereignty over it.

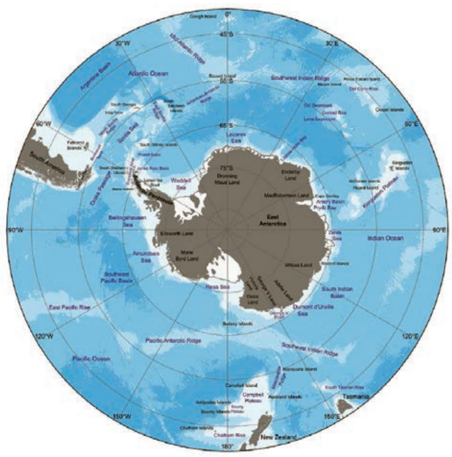

Fig.1 — The Southern Ocean (De Broyer *et al.*, 2014).

Antarctica and the Southern Ocean have not always been extreme environments. Antarctica used to be more temperate when it belonged to Gondwana, the great southern continent. Nearly 34 million years ago (Crame, 2014), it gradually detached from the other southern hemisphere continents which had allowed the opening of the Drake Passage. The Southern Ocean became hydrologically isolated with more than 4°C cooling of surface waters. This is when the formation of sea ice is supposed to have begun. Observations suggest several cooling events causing significant faunal changes with the extinction of a number of species (Crame, 2014).

The knowledge of this history is important to understand what the consequences of climate change could be on a biodiversity that has adapted to extreme conditions over such a long period. It is therefore necessary to assess the present state of the Southern Ocean marine biodiversity. All present knowledge on biodiversity has been compiled in the recent biogeographic atlas of the Southern Ocean (De Broyer *et al.*, 2014). Our knowledge began with the scientific expeditions conducted in 1772-1775 by Captain James Cook. It increased with numerous famous missions at sea (De Broyer *et al.*, 2014) until the recent International Polar Year (2007-2009) with the "Census of Antarctic Marine Life" program (2005-2010). During this program, 18 research vessels sailed the Southern Ocean to study all aspects of its biodiversity. The phylogeny of these species was also assessed. At a global level, species biogeography had to be ascertained by studying their potential habitats using statistical analysis and modelling tools, similarly to Cuzin *et al.* (2014) for euphausiids (krill), Duhamel *et al.* (2014) for fish or Eléaume *et al.* (2014) and Saucède *et al.* (2014) for echinoderms, for example. Obviously, temperature is one of the major factors controlling the biogeography of these species. Several studies have attempted to define ecoregions characterized by their abiotic hydrological and geographical features (Longhurst, 2007; Raymond, 2014) and by differences in prevailing species assemblages (Koubbi *et al.*, 2011; Hosie *et al.*, 2014). Despite these efforts, many unexplored regions still exist both along the Antarctica coastline as well as offshore. Moreover, deep waters generally still remain poorly understood in spite of many recent studies (Brandt *et al.*, 2014; Rogers and Linse, 2014).

While it is necessary to consider the consequences of environmental change, this concern should be rapidly included in ecosystem management programs by the evaluation of areas to be protected. However, the limits of the Southern Ocean and the reasons why its biodiversity is so exceptional should first be defined.

WHAT ARE THE TYPICAL BOUNDARIES OF HABITATS IN THE SOUTHERN OCEAN?

The definition of oceanic regions begins with the analysis of oceanographic data (Post *et al.*, 2014). The Southern Ocean communicates in the North with the Atlantic, Indian and Pacific Oceans.

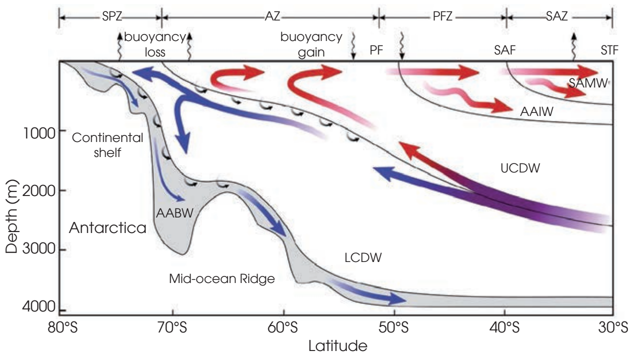

Fig.2 — Latitudinal section showing the water masses and fronts as a function of depth from the Antarctic continent to the Sub-Tropical Front (STF) (Post *et al.*, 2014.). The Antarctic Polar Front (APF) and the Sub-Antarctic Front (SAF) are shown. The fronts delimit different areas: the Sub-Antarctic zone (SAZ), the Polar Frontal Zone (PFZ), the Antarctic Zone (AZ) and Sub-Polar Zone (SPZ). The different water masses are illustrated: the Sub-Antarctic Modal Water (SAMW), the Antarctic Intermediate Water (AAIW), the Upper Circumpolar Deep Water (UCDW), the Lower Circumpolar Deep Water (LCDW) and the Antarctic Bottom Water (AABW). The arrows indicate the flow of water masses. Note that Antarctic Bottom Water is formed on the continental shelf and then circulates deeply.

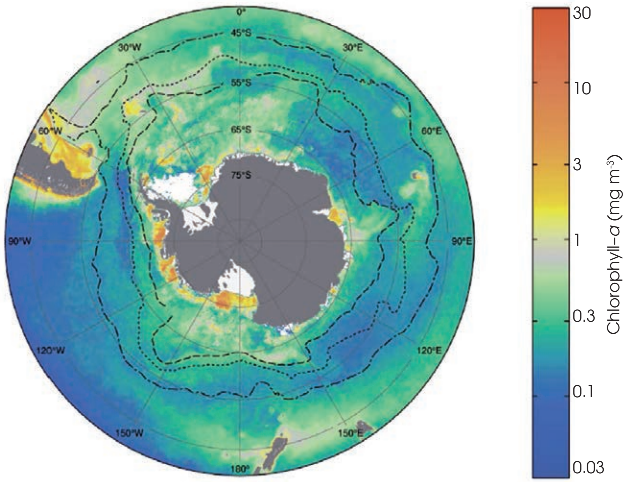

Fig.3 — Average summer chlorophyll a concentrations between 2002 and 2010 estimated by Aqua MODIS satellite data (Post *et al.*, 2014.). From South to North, the dotted lines mark the southern boundary of the Antarctic Circumpolar Current, the average position of the Antarctic Polar Front and Sub-Antarctic Front, respectively.

There are several major fronts in the Southern Ocean (figure 2). First of all, the Subtropical Front (STF) is defined as the northern limit of this ocean. Heading southwards, the Sub-Antarctic Front (SAF) and the Antarctic Polar Front (APF) are encountered. The Sub-Antarctic Zone extends between the STF and the SAF, the Polar Frontal Zone between the APF and SAF and the Antarctic area south of the APF. Further south, other fronts mark the southern boundary of the Antarctic Circumpolar Current. These fronts cannot be considered as fixed barriers, as they vary latitudinally according to seasonal climate forcing. Some of these fronts are the site of intense phytoplankton production that induces secondary plankton production (figure 3). This is the case in the vicinity of Sub-Antarctic Islands that enrich the environment with iron and other nutrients useful for phytoplankton growth. The area South of these islands, between the northern limit of the APF and the boundary of the seasonal ice zone, is under the influence of the Antarctic Circumpolar Current, with permanently open sea and no ice-cover. This is a particular area as it is characterized as a HNLC region with high nutrient concentrations but low chlorophyll or phytoplankton concentrations. This can be explained by the lack of certain essential elements, such as iron, that limit phytoplankton growth.

However, more than half of the Southern Ocean is characterized by a seasonal ice zone (figure 4) around the Antarctic continent. The highest concentrations in chlorophyll a, are observed during the summer (figure 3). Significant changes in the extent, in the duration of sea ice or in its thickness have been observed at the West Antarctic Peninsula, where the area of sea ice has been observed to decrease by 5 to 6% per decade. However, this trend does not apply all around the continent since, conversely, an increase of 4.5 to 5% has been observed in the Ross Sea, (Constable *et al.*, 2014). Sea ice extent is not the only factor to take into account. The duration of the presence of seasonal sea ice has also decreased in the Western region of the Antarctic Peninsula with an equivalent loss in number of days to what has been observed in the Arctic. Once again, these are regional observations, since opposite observations have been made in other sectors,

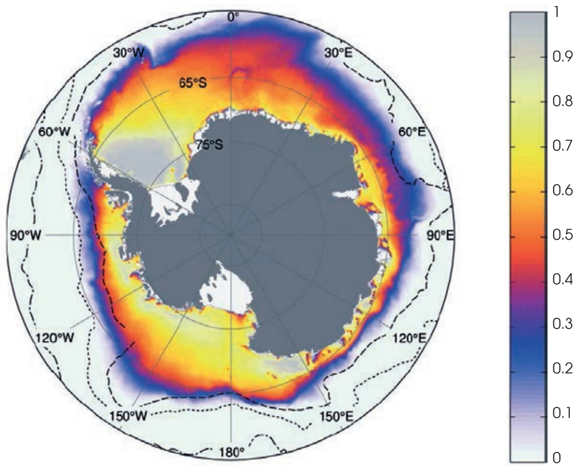

Fig.4 — Map of the proportion of 85% concentration of annual sea ice duration (Post et al, 2014.). Polynyas are visible along the continent (blue colours). Dashes indicate the position of the southern front of the Antarctic Circumpolar Current; the dots represent the average position of the Antarctic Polar Front and the dotted line with dashes in the North, the position of the Sub-Antarctic Front.

thus showing that the development of the sea ice involves different factors. Close to the continent, a number of areas are free of ice either all year round or periodically. These areas, called polynyas, are often located in the coastal zone where the topography and prevailing winds prevent sea ice from accumulating (figure 4). Polynyas have an important role for biological production, as during spring they allow light to penetrate into the water while the adjacent ice-covered areas remain in the dark. The onset of primary production comes with the first signs of spring and as the ice begins to break, thus feeding both the pelagic and benthic ecosystems.

Longhurst, in the "Ecological Geography of the Sea," identified four so-called "biogeochemical" provinces within the polar biome including the Southern Ocean. These provinces have been appointed respectively: South Subtropical Convergence province (SSTC), Sub-Antarctic water ring Province (SANT), Antarctic province (ANTA) and Polar Southern Province (APLR) (figure 5). Each of these provinces theoretically delimits the particular types of environmental or hydrological forcing that can be encountered. Longhurst spatially defined the distribution of these provinces using satellite observations combined with oceanographic and biological samples collected during cruises.

Recently, Reygondeau and Huettmann (2014) have statistically characterized these biogeochemical provinces. The methodology they developed was used to assess the changes in the spatial distribution of these 4 provinces as a function of seasonal and interannual variations (Reygondeau *et al.*, 2013) or over a long-term. The results of the study presented in figure 5 point to a poleward shift of all southern provinces. However, the speed of change appears to be different between provinces (figure 6). In fact, the Sub-Antarctic provinces (SSTC and SANT) seem to be most strongly affected by variations in the environmental conditions induced by climate change. Their distribution centres are more rapidly displaced southwards than the polar provinces (ANTA and APLR). These changes result in a drastic reduction (approximately 15%) of the total area of the Sub-Antarctic zone while the northern Subtropical systems are expanding. Only the Southern zones maintain their initial characteristics (loss <5% of their areas).

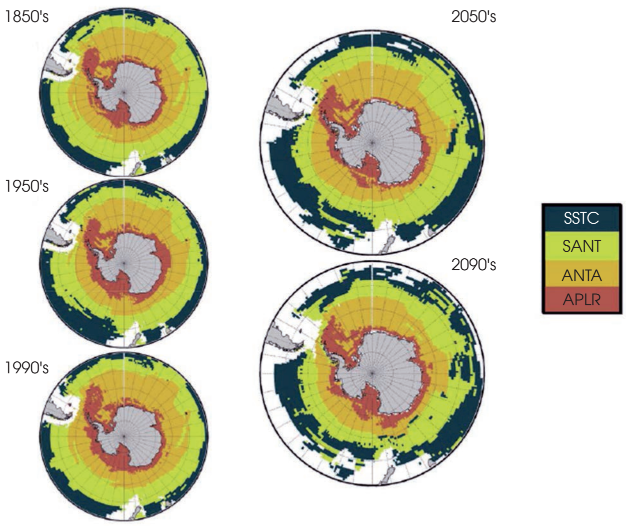

Fig.5 — Distribution of biogeochemical provinces of the Southern Ocean for the 1850, 1950 and 1990 decades as well as their projection for 2050 and 2100 (Reygondeau and Huettmann, 2014). The current provinces have been defined by Longhurst (2007).

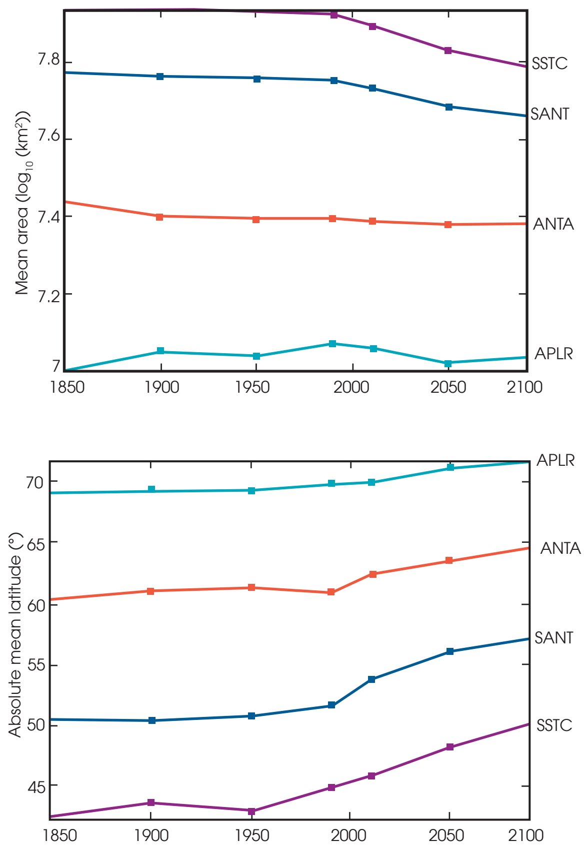

Fig.6 — Evolution of the mean absolute latitude and area of each biogeochemical province (Reygondeau and Huettmann, 2014).

These observed changes in biogeochemical provinces of the Southern Ocean can be directly connected to the various effects caused by climate change. Analyses carried out under the NEREUS consortium (figure 7) used a set of environmental parameters that structure the marine environment (temperature, salinity, oxygen concentration, primary production, pH, % ice cover and U and V direction components of currents). Results confirm the spatial heterogeneity of the amplitude and driving forces of climate change in the Southern Ocean. Areas further North (sub-Antarctic areas) have been most severely affected by the different effects of climate change (figure 7a) and particularly by the increase in sea surface temperatures (figure 7b). The more southerly zones (ANTA and APLR) appear to remain best preserved from the severity of global change. However, certain parameters presenting a structural role in the development of marine species seem to have been altered in these latter areas (figure 7b). In fact, despite lesser variations compared to the sub-Antarctic areas, the changes in ice-cover, surface temperature and pH and primary production in the southern areas are significant. Even though the magnitude of these changes remains lower than that of the sub-Antarctic areas, like a sword of Damocles, their effects hang over the endemic organisms that are adapted to extreme conditions, thus menacing the biodiversity of these areas.

A UNIQUE BIODIVERSITY CONFRONTED TO MAJOR CHANGES

The different species in the Southern Ocean have adapted to extreme living conditions. Although the degree of impact of global warming varies according to the area in the Southern Ocean, it is particularly significant in the Antarctic Peninsula and around the sub-Antarctic islands (Constable *et al.*, 2014). Exposure to UV radiation has increased due to the presence of the Ozone Hole whose extent is at its maximum during the southern hemisphere spring season. Acidification has also become a new threat. Species habitats, ecosystems and food webs mechanisms are likely to suffer from these changes. Moreover, a number of anthropogenic impacts add to these threats, such as the exploitation of living resources.

Antarctic benthos

The Antarctic benthos is characterized by large biodiversity, a high endemism and, in some areas, the highest observed levels of biomass. In terms of composition, some groups are absent or poorly represented in the Southern Ocean (stomatopods, balanomorph barnacles, decapod "walkers", bivalves). Brachyuran crabs are totally absent from the Antarctic region while there is fossil evidence of their presence before

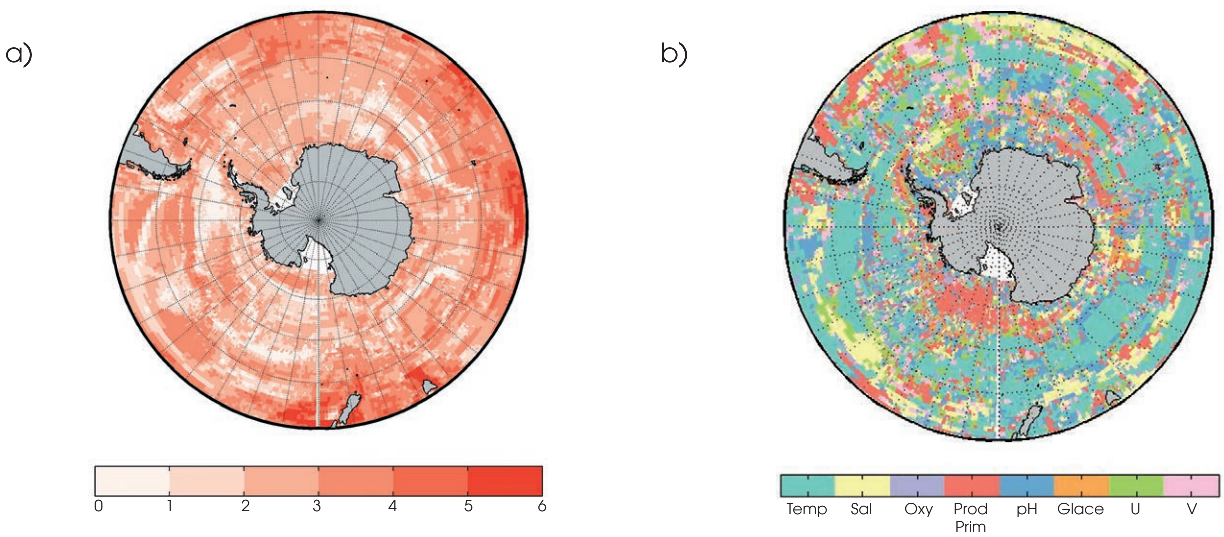

Fig.7 — (a): Status of environmental disturbances and (b) structuring parameter changes. Temperature (Temp), Salinity (Sal), oxygen concentration (0_2), Primary production (PP), pH; % ice cover; U and V, components of the current.

polar waters cooled down during the Cenozoic. Other groups, however, have radiated intensely in these waters. It is the case of the highly diverse pycnogonids, amphipods and isopods, probably partly due - for the latter two groups – to the occupation of niches left vacant by the disappearance of the decapods.

Nowadays, species diversity of the Antarctic benthos appears to have been largely underestimated. Firstly, the molecular approach has highlighted many cryptic species (Held, 2014; Eléaume *et al.* 2014; Havermans, 2014.) Secondly, large areas of the Southern Ocean still remain to be documented, in particular the deep waters where the first systematic surveys have yielded the existence of many unknown species (Brandt *et al.*, 2014).

The molecular approach has also challenged the paradigm of a circumpolar distribution of benthic species: many species, initially considered as circumpolar or even cosmopolitan, have proved to rather represent species complexes with a restricted and often allopatric distribution. Nonetheless, the same molecular approach also confirmed the broad circumpolar distribution of other species.

The macrobenthic populations of the continental shelf can be remarkably abundant: in some parts they even erect massive biological structures, essentially composed of suspension feeders such as sponges, bryozoans, hydrocorals, ascidians or crinoids. These represent a three-dimensional substrate, a food resource as well as symbiotic opportunities for many other organisms. Nevertheless, the spatial distribution of these populations, as well as their composition, abundance and biomass, or their eco-functional role can all vary greatly according to the depth or geography (Gutt *et al.*, 2014).

The potential impacts of climate change (temperature, pH, ice cover, iceberg scouring, quantity and quality of food resources) on benthic communities are still difficult to determine. There remains a lack of sufficient knowledge on the life cycles and eco-functional role of benthic species, on their different degrees of sensitivity to environmental factors involved, on their multiple interactions, as well as on the different spatial and temporal scale factors governing the great diversity of benthic populations (see Ingels *et al.*, 2012).

Recent experimental approaches on the potential vulnerability of selected benthic organisms (sea urchins, foraminifera...) towards the impacts of physical changes in the environment (especially temperature increase and fall in pH) have clearly evidenced the lethal physiological and functional limits of these endemic species (Peck *et al.*, 2010). However, these results cannot yet be generalised to the entire benthic biodiversity (Kaiser *et al.*, 2013).

The scouring of the seabed by icebergs is a physical process that most strongly affects the benthic communities of the Antarctic continental shelf down to 300 m depth or more. Increasingly warmer waters now tend to undermine the base of the ice shelves surrounding the continent, leading to an increase in the calving of icebergs with a subsequently greater impact on the pericontinental benthos.

Demersal Antarctic Fish

The case of Antarctic demersal fish is also unique. Their evolutionary history has been studied and one of its groups, the Notothenioidei are nearly 86% endemic to the Southern Ocean (Duhamel *et al.*, 2014). Originally derived from temperate waters, they adapted to the Southern Ocean during its cooling period. The most polar species have thus developed antifreeze glycoproteins that prevent their blood and tissues from crystallizing in freezing sea water temperatures. During the cooling period, these fish colonized all available ecological niches that were left following the extinction of other species that were incapable of adapting to this change. Certain Notothenioidei species are endemic to their region or to their island, while others are circumpolar, surviving both in stable environments (such as in sponges) or in disturbed environments (e.g. icebergs). Some species of fish, like the cryopelagic fish *Pagothenia borchgrevincki* can even survive in the sea ice. A few species are commercially exploited such as the Antarctic toothfish or the Patagonian toothfish. Some of these fish, have been living in waters with low thermal variations and have lost their physiological ability to adapt to the warming environment. At present, the ecological and economic consequences of global warming still remain difficult to conceive.

Pelagic organisms

The spatio-temporal patterns that influence pelagic organisms, whether they are plankton, pelagic fish or cephalopods, are closely related to the structures of water masses, to the currents, and to the characteristics of the frontal zones and seasonal dynamics of the ice. To date, knowledge on pelagic species is mostly restricted to the epipelagic zone where the penetration of sunlight supports phytoplankton photosynthesis. Yet little is known of the deeper areas such as the mesopelagic zone where many predators prey on the very abundant mesopelagic fish.

Studies in recent decades have shown that the SAF is a major biogeographical front for several sectors of the Southern Ocean. This has been observed by Hosie *et al.* (2014) for plankton or Koubbi (1993) and Duhamel *et al.* (2014) for mesopelagic fish. The STF and APF have already been considered as such for a long time. The latitudinal distributions of many pelagic species (Atkinson *et al.*, 2012 ; Hunt and Hosie, 2005, 2006a, b) that are essential for the good functioning of the food web can be explained by the position of the three northern fronts of the Southern Ocean (STF, SAF and APF), the extent of seasonal ice and the Antarctic continental shelf. These species comprise copepods (Hosie *et al.*, 2014), euphausiids which include Antarctic krill and ice krill (Cuzin *et al.*, 2014), or mesopelagic fish (Koubbi *et al.*, 2011 and Duhamel *et al.*, 2014). In addition, there are regional peculiarities around the sub-Antarctic islands. For example, endemic species such as the planktonic copepods *Drepanopus pectinatus* can be found in the vicinity of the Crozet, Kerguelen and Heard Islands. These endemic species are not necessarily locally rare as this type of copepod dominates more than 90% of the whole zooplankton pool of the Bay of Morbihan in the Kerguelen Islands (Razouls and Razouls, 1990). Nonetheless, how they will adapt to the rise in temperatures is still uncertain. From the sub-Antarctic Zone to the continent, the distribution of pelagic species is expected to shift southwards concurrently with the southward displacement of the frontal zones (Constable *et al.*, 2014). Neritic species (associated with islands or continental shelves), however, do not migrate, which implies that the pelagic environment of many sub-Antarctic islands might undergo profound modifications.

On the Antarctic continental shelf, ice krill is dominant, while Antarctic krill takes over at the slope. This symbolic species of the Southern Ocean is greatly abundant, especially in the Atlantic sector of the Southern Ocean in the Scotia Sea and Antarctic Peninsula. Antarctic krill strongly depend on winter ice conditions that are important for their reproduction, their survival and the development of the young stages. Krill densities have fallen by almost 30% since the 1980s (Atkinson *et al.*, 2004). Reasons for explaining this decrease could primarily be the reduction in the duration and northward extension of the icecap. However, other hypotheses have been proposed, such as modifications in the abundance of predators and the increase in whale populations (Murphy *et al.*, 2012). Current preoccupations attempt to understand how the Antarctic krill-based pelagic food web might, under the effect of global warming, convert into a food web based on other species like copepods and lantern fish for example, as observed in the Polar Frontal Zone. In addition, the proliferation of gelatinous organisms such as salps might dominate the ecosystem during "warmer" episodes. This would result in years when krill abundances would be lower, while salps would unfortunately not be interesting targets for predators.

In this sea ice zone , several species spend all or part of their life cycle under the ice or in its fractures (Swadling *et al.*, 2014). Some of these species are able to adjust the duration of their various development stages to the dynamics of sea ice. For example, for the copepod *Paralabidocera antarctica*, the duration of its copepodite stages varies in conjunction with the duration of the presence of sea ice from one region of East Antarctica to another (Loots *et al.*, 2009, Swadling *et al.*, 2014). This plasticity, however, does not exist for all species.

Seabirds

With new satellite telemetry technology and marine observations, the distribution of birds and marine mammals at sea and throughout all seasons can be monitored. There are as many answers as there are species. Current and future changes are expected to alter either the habitats of these species or their tolerance and adaptation to abiotic conditions (Constable *et al.*, 2014). In the Antarctic Peninsula, declining Adelie penguin populations seem to be related to the decrease in the extent of sea ice. This differs from observations in the Ross Sea and parts of East Antarctica where ice conditions are different (Constable *et al.*, 2014). These current signs suggest that the major change should concern food webs. The trophic habitats of certain species are pelagic and depend on oceanographic structures such as fronts. For example, the Crozet Island King penguins feed south of the archipelago, in the APF area, where the mesopelagic fish that they catch are more abundant and accessible. Should the forecasted variations occur, the southward shifting of the APF will double the travelling distance for these penguins to their fishing grounds (Peron *et al.*, 2012).

PROTECT AND MONITOR ECOSYSTEMS

The major changes that have been observed for nearly 30 years are therefore essentially related to the increase in temperature, resulting in a southward shift of the frontal zones and areas described above. These changes are not uniform across the whole Southern Ocean but can reach various degrees of importance depending on the region (Constable *et al.*, 2014). Among these changes, the increase in atmospheric carbon dioxide and its absorption by the Southern Ocean causes seawater acidification (Midorikawa *et al.*, 2012). As the solubility of CO2 is higher in cold water, polar waters attack organisms with calcium carbonate shells more easily, including pteropod molluscs. These planktonic organisms are covered by a thin shell and they have an essential role as herbivores (Roberts *et al.*, 2014). Benthic invertebrates with calcified shells are also affected.

Assumptions can be made about the coming changes that the Southern Ocean will undergo. It is necessary to protect marine areas that are most outstanding for their biodiversity and also the most vulnerable. Reference scientific zones should also be established, where human impact would be reduced, so as to monitor the variations in ecosystems due to climate change. The CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources) aims at assessing the marine resources of the Southern Ocean each year using an Ecosystem Approach. As part of the Antarctic Treaty system, the CCAMLR has set up monitoring programs to detect changes in the marine ecosystem (www.ccamlr.org). More recently, the CCAMLR has undertaken to define a representative system of Marine Protected Areas (MPAs). Although various MPAs have been declared around the Sub-Antarctic Islands by their sovereign states, the offshore waters outside national jurisdiction can only be protected by the consensus of the 25 members at the head of the CCAMLR. Consequently, in 2009, CCAMLR defined a first MPA of 94,000 km² surrounding the South Orkney Islands. Other candidate areas are being proposed, such as East Antarctica, the Ross Sea and soon the Weddell Sea and the Antarctic Peninsula. On each of these sectors, the objective is to maintain the biodiversity that is representative of these regions and to propose scientific reference zones. However, the outcome of these negotiations is difficult and might even last a very long time. It is crucial to justly take into account the impacts of climate change for conservation.

In the meantime, it is necessary to carry out long term monitoring of the marine ecosystem. Several international programs have been developed under the auspices of the SCAR (Scientific Committee on Antarctic Research). The SOOS program (Southern Ocean Observing System), for example, encourages the monitoring of physical, chemical and biological parameters. Another SCAR program is the SO-CPR (Southern Ocean Continuous

Plankton Recorder). The Continuous Plankton Recorder (CPR) has been used since the 1930s in the North Atlantic and has highlighted major changes in plankton communities in the Atlantic Ocean. The SO-CPR program began in 1991. Monitoring is mainly carried out on research vessels from different countries, including the "R/V Marion Dufresne" since 2013, around the French Southern and Antarctic Territories. Nearly 200 planktonic taxa have been identified in this program, which allowed the study of the spatial distribution of zooplankton as well as its seasonal and inter-annual variability. Latitudinal variations of monthly assemblages of zooplankton have been revealed by Hosie *et al.* (2014). In France, this program is part of the CNRS "Zone Atelier Antarctique" http://za-antarctique.univ-rennes1.fr. Its objectives involve the development and maintenance of a long-term observation network of polar biodiversity using the principle of LTER (Long Term Ecological Research). Research laboratories involved in the program benefit from the logistical support of the French Polar Institute: IPEV (Institut Paul Emile Victor, www.ipev.fr).

These national and international initiatives and the few examples mentioned above are essential to understand the effects of climate change, not only at the scale of the Southern Ocean but also at a regional level. Indeed, important distinctions can be made between the sub-Antarctic islands, the Antarctic Peninsula, East Antarctica and other areas of this ocean. While we are just starting to sense the consequences of these changes on the surface waters, it remains crucial to study the deep benthic and pelagic environments.

RÉFÉRENCES

- ATKINSON A., SIEGEL V., PAKHOMOV E.A., JESSOPP M.J., LOEB V., 2009 – *A Re-Appraisal of the Total Biomass and Annual Production of Antarctic Krill*. Deep-Sea Research Part I-Oceanographic Research Papers 56, 727–740.
- ATKINSON A., WARD P., HUNT B.P.V., PAKHOMOV E.A., HOSIE G.W., 2012 – *An Overview of Southern Ocean Zooplankton Data: Abundance, Biomass, Feeding and Functional Relationships*. CCAMLR Science 19, 171–218.
- BRANDT A., VAN DE PUTTE A.P., GRIFFITHS H.J., 2014 – *Southern Ocean Benthic Deep-Sea Biodiversity and Biogeography*. In Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, 233-239.
- CONSTABLE A.J., MELBOURNE-THOMAS J., CORNEY S.P., ARRIGO K.R., BARBRAUD C. *et al.*, 2014 – *Climate Change and Southern Ocean Ecosystems I: How Changes in Physical Habitats Directly Affect Marine Biota*. Global Change Biology: DOI: 10.1111/gcb.12623
- CRAME A., 2014 – *Evolutionary settings*. In Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, 32-35.
- CUZIN-ROUDY J., IRISSON J.-O., PENOT F., KAWAGUCHI S., VALLET C., 2014 – *Southern Ocean Euphausiids*. In Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, 309-320.
- DE BROYER C., KOUBBI P., GRIFFITHS H.J., RAYMOND B., UDEKEM D'ACOZ C. D' *et al.*, 2014 – *Biogeographic Atlas of the Southern Ocean*. Scientific Committee on Antarctic Research, Cambridge, XII+498 pp.
- DUHAMEL G., HULLEY P.-A., CAUSSE R., KOUBBI P., VACCHI M. *et al.*, 2014 – *Biogeographic Patterns of Fish*. In Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, 328-362.
- ELÉAUME M., HEMERY L.G., AMÉZIANE N., ROUX M., 2014 – *Phylogeographic Patterns of the Southern Ocean Crinoids (Crinoidea: Echinodermata)*. In Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, 448-455.
- GUTT J., BARNES D.K.A., LOCKHART S.J., 2014 - Classification and spatially explicit illustration of Antarctic macrobenthic assemblages: A feasibility study. In Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, 229-232.
- HAVERMANS C., 2014 – *Phylogeographic Patterns of the Lysianassoidea (Crustacea: Peracarida: Amphipoda)*. In Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, 441-447.

- HELD C., 2014 – *Phylogeography and Population Genetics*. In Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, 437-440.
- HOSIE G., MORMÈDE S., KITCHENER J., TAKAHASHI K., RAYMOND B., 2014 – *Near Surface Zooplankton Communities*. In Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, 422-430.
- HUNT B., HOSIE G., 2005 – *Zonal Structure of Zooplankton Communities in the Southern Ocean South of Australia: Results from a 2 150 Km Continuous Plankton Recorder Transect*. Deep-Sea Research I 52, 1241–1271.
- HUNT B., HOSIE G., 2006a – *The Seasonal Succession of Zooplankton in the Southern Ocean South of Australia, Part I: the Seasonal Ice Zone*. Deep Sea Research I 53, 1182–1202.
- HUNT B., HOSIE G., 2006b – *The Seasonal Succession of Zooplankton in the Southern Ocean South of Australia, Part Ii: the Sub-Antarctic to Polar Frontal Zones*. Deep Sea Research I 53, 1203–1223.
- INGELS J., VANREUSEL A., BRANDT A., CATARINO A.I., DAVID B. *et al.*, 2012 – *Possible Effects of Global Environmental Changes on Antarctic Benthos: a Synthesis Across Five Major Taxa*. Ecology and Evolution 2(2): 453–485.
- KAISER S., BRANDAO S.N., BRIX S., BARNES D.K.A., BOWDEN D.A. *et al.*, 2013 – *Patterns, Processes and Vulnerability of Southern Ocean Benthos: a Decadal Leap in Knowledge and Understanding*. Marine Biology 160 (9): 2295-2317.
- KOUBBI P., 1993 – *Influence of the Frontal Zones on Ichthyoplankton and Mesopelagic Fish Assemblages in the Crozet Basin (Indian Sector of the Southern Ocean)*. Polar Biology 13(8): 557-564.
- KOUBBI P., MOTEKI M., DUHAMEL G., GOARANT A., HULLEY P.A. *et al.*, 2011 – *Ecoregionalisation of Myctophid Fish in the Indian Sector of the Southern Ocean: Results from Generalized Dissimilarity Models*. Deep-sea Research II 58: 170-180.
- LONGHURST A., 2007 – *Ecological Geography of the Sea*. 2 ed., London: Academic Press, London, 390 pp.
- LOOTS C., SWADLING K.M., KOUBBI P., 2009 – *Annual Cycle of Distribution of Three Ice-Associated Copepods Along the Coast Near Dumont D'urville, Terre Adelie (Antarctica)*. Journal of Marine Systems 78(4): 599-605.
- MIDORIKAWA T., INOUE H.Y., ISHII M. *et al.*, 2012 – *Decreasing pH Trend Estimated from 35-Year Time Series of Carbonate Parameters in the Pacific Sector of the Southern Ocean in Summer*. Deep Sea Research I 61: 131–139.
- MURPHY E.J., CAVANAGH R.D., HOFMANN E.E. *et al.*, 2012 – *Developing Integrated Models of Southern Ocean Food Webs: Including Ecological Complexity, Accounting for Uncertainty and the Importance of Scale*. Progress in Oceanography 102: 74–92.
- PECK L.S., MORLEY S., CLARK M., 2010 – *Poor Acclimation Capacities in Antarctic Marine Ectotherms*. Marine Biology 157(9): 2051-2059.
- PÉRON C., WEIMERSKIRCH H., BOST C.A., 2012 – *Projected Poleward Shift of King Penguins´ (Aptenodytes Patagonicus) Foraging Range at the Crozet Islands, Southern Indian Ocean*. Proceedings of the Royal Society B 279: 2515–2523.
- POST A.L., MEIJERS A.J.S., FRASER A.D., MEINERS K.M., AYERS J. *et al.*, 2014 – *Environmental Settings*. In Biogeographic Atlas of the Southern Ocean. Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, 46-64.
- RAYMOND B., 2014 – *Pelagic Regionalisation.* In Biogeographic Atlas of the Southern Ocean. Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, 418-421.
- RAZOULS C., RAZOULS S., 1990 – *Biological Cycle of a Population of Subantarctic Copepod, Drepanopus pectinatus (Clausocalanidae), Kerguelen Archipelago*. Polar Biology 10: 541–543.
- REYGONDEAU G., LONGHURST, A., MARTINEZ, E., BEAUGRAND, G., ANTOINE, D., MAURY, O., 2013 – *Dynamic Biogeochemical Provinces in the Global Ocean*. Global Biogeochemical Cycles 27: 1046-1058.
- REYGONDEAU G., HUETTMANN F. 2014 – *Past, Present and Future State of Pelagic Habitats in the Antarctic Ocean. in Biogeographic Atlas of the Southern Ocean*. Scientific Committee on Antarctic Research, Cambridge, 397-403.
- ROBERTS D., HOPCROFT R.R., HOSIE G.W., 2014 – *Southern Ocean Pteropods*. In Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, 276-283.
- ROGERS A.D., LINSE K., 2014 – *Chemosynthetic Communities*. In Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, 240-244.
- SAUCEDE T., PIERRAT B., DAVID B., 2014 – *Echinoids*. In Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, 213-220.
- SWADLING K.W.., 2014 – *Sea-Ice Metazoans*. In Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge, 321-325.

The Arctic: Opportunities, Concerns and Challenges

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The Arctic is often thought of as the land of polar bears and explorers. There are already several industries operating in the Arctic, through the Arctic, or at the periphery of the Arctic Circle. Receding and thinning sea ice with climate change provides increased access to natural resources, shipping routes and touristic areas, thereby providing new opportunities for economic development in the Arctic. The rewards for operating in the Arctic are potentially extremely high and attractive, but at high financial, environmental and social costs in an environment which remains financially very risky. Some stakeholders have started securing access to Arctic resources, sowing the seeds for a 'cold rush'. Such 'cold rush' has not materialised yet, slowed down because of high economic costs and political sensitivity. The main political challenge ahead is to successfully reconcile the different perspectives and interests in the Arctic. One option to facilitate this reconciliation is to build up existing institutional capacity in line with the pace of economic development. There is certainly strong potential for creating shared economic wealth and well-being. Actual choices made by Arctic industries and countries for economic development, coordination and cooperation for establishment of environmental and social safeguards within the coming years will shape what the future Arctic will look like.

The Arctic refers to an oceanic area around the North Pole and Arctic Circle partly covered in sea ice and surrounded by frozen lands. The Arctic is made of two zones: the Arctic Ocean and the Arctic region. The Arctic Ocean is bordered by five sovereign states (United States of America, Canada, Denmark, Norway, and the Russian Federation) subject to international law of the sea (in particular under the United Nations Convention on the Law of the Sea, UNCLOS, of 10 December 1982). The Arctic region is broader and encompasses all states which have land in the Arctic Circle. The Arctic region includes all five states bordering the Arctic Ocean, with the addition of Iceland, Finland and Sweden. There is no agreed delineation of an 'Arctic Region' and population estimates vary from 4 to 10 million depending on the geographic extent considered (Ahlenius *et al.*, 2005, p.6 & 14; Norway Ministry for Foreign Affairs, 2015, p.5; Duhaime and Caron, 2006).

The Arctic is part of the global climate system with heat redistribution through ocean currents between the North Pole and the equator, as well as heat and nutrient redistribution between surface waters and the deep abyssal plains (Ocean and Climate, 2015). Impacts from climate change in the Arctic are stronger and faster than any other areas of the globe. The Arctic is therefore seen as the ‘canary in the mine’, an early warning sentinel of climate change impacts (The Arctic – The Canary in the Mine. Global implications of Arctic climate change. Norwegian-French conference in Paris, 17 March 2015).

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

Such changes in the Arctic open up access to Arctic ocean-floor resources and sea routes, with new opportunities for economic development in the region which could impact global trade patterns and trends (Valsson and Ulfarsson, 2011). If left open and uncoordinated, such economic development has the potential to lead to a wild ‘cold rush’ driven by selfish interests rather than a concerted effort to make the most of these new opportunities for society as a whole and create shared wealth and well-being.

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

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

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

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

(Glomsrød and Aslaksen, 2009; Ahlenius *et al.*, 2005, p.27). Such subsistence activities are associated with significant traditional trading and bartering between different Arctic populations (Figure 1; Glomsrød and Aslaksen, 2009).

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

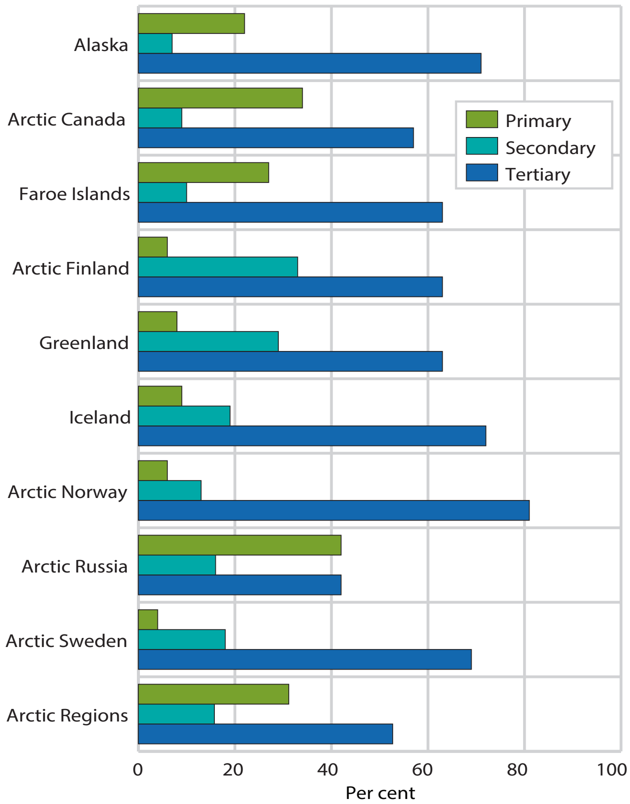

Fig.2 — GDP (%) by main industry in the different Arctic Regions (reference year: 2003) (Source: Duhaime and Caron, 2006, Figure 2.1 p.19). Primary sector: large-scale extraction of non-renewable resources, small-scale commercial fishing and forest exploitation; secondary sector: manufacturing and construction;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

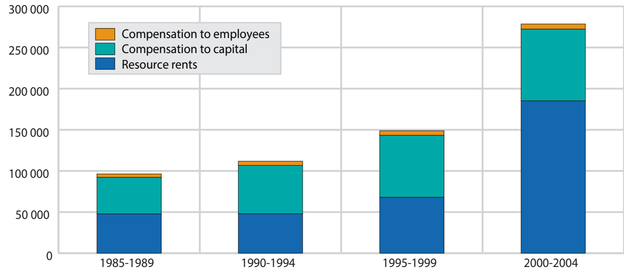

Fig.3 — Five-year average decomposition of gross production in the Norwegian oil and gas (offshore) sector (Source: Duhaime and Caron, 2006, Figure 1 p.24).

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

The Arctic has limited shipping activity dominated by population resupply along the Northern Sea Route and Northwest passage, fishing in the ice-free waters around Iceland and in the Bering, Barents and Norwegian Seas, and tourism along the coasts of Northern Norway, Southwest Greenland and Svalbard (Peters *et al.*, 2011). Bulk cargo is associated with large mining operations in Alaska (zinc) and Russia (mainly nickel) and limited oil and gas transport mostly taking place on the Eurasian side (Peters *et al.*, 2011).

LOCAL OPPORTUNITIES FOR DEVELOPMENT OF ECONOMIC ACTIVITIES ARISING WITH CLIMATE CHANGE IN THE ARCTIC: POTENTIALLY HIGH ECONOMIC BENEFITS FOR HIGH ECONOMIC COSTS IN A HIGH-RISK ENVIRONMENT

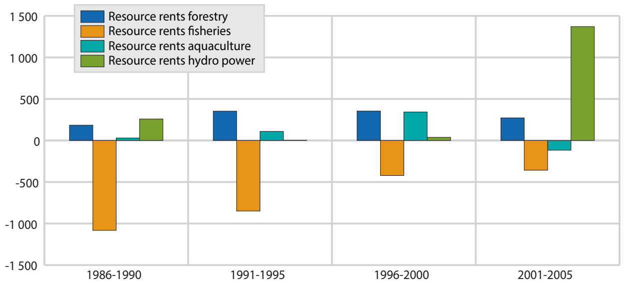

Fig.4 — Five-year average resource rents from the renewable natural resources in Norway (Source: Duhaime and Caron, 2006, Figure 2 p.25).

All industries operating in the Arctic region are faced with slightly different opportunities and constraints arising because of climate change in the Arctic, associated with potentially high economic benefits but for high economic costs in an environment that is financially risky to operate in. The receding ice sheet cover allows for increased physical access to natural resources such as fish and timber (renewable resources), oil, gas and minerals (non renewable resources). Such increased access could translate into additional economic revenues for the fish, timber, mining (oil & gas, minerals) industries. Economic opportunities arise mainly with increased physical access or access time to quantities of natural resources, not so much because of increases in market prices.

Most of the following descriptions and numbers rely on the use of models for predictions of future outcomes and are often subject to a high level of uncertainty. The quality of the outputs from such models depends on data quality, trends and understanding at the time the models were established. The predictions from such models should be considered with caution, especially when very optimistic, as they may not fully materialise, or only in 2030-2050. The second difficulty in judging actual opportunities is based on the fact that the numbers of potential gains put forward are not always based on evidence but rather on perceptions.

The **shipping (sea transport) industry** would benefit from greater use of Arctic and circumpolar (sea transport) shipping routes such as the Northern Sea Route (the shipping lane along the Russian Arctic coast that connects Europe to the Asia-Pacific region), the Northwest passage (along the North American coastline), or the Bering Strait (53-mile strait between Siberia and Alaska) thanks to reduced ice cover extent and thickness and longer ice-free periods increasing seasonal availability to maritime traffic (Conley *et al.*, 2013, p.32-37; Peters *et al.*, 2011). These routes cut down miles, shipping time and fuel costs, which combined with high fuel costs increase their appeal to the industry. Estimates of 40% shipping cost saving and recent cost saving 'records' between Europe and Asia are widely quoted to illustrate the economic potential of these routes. More recent studies accounting for ship performance in ice conditions are far less optimistic with only 5-16% cost saving now, and up to 29% in 2030 and 37% in 2050 (Peters *et al.*, 2011; Liu and Kronbak (2010). Actual cost saving needs to be traded off with the higher costs for ice class ships, non-regularity and slower speeds, navigation difficulties and risks of accidents from poor visibility and ice conditions, as well as the need for extra ice breaker service (Liu and Kronbak, 2010). There are a limited number of public-use deep-water ports, re-fuelling stations, or reliable re-supply locations, limited communications and emergency response infrastructure including search and rescue capacity in the Russian Federation and Northern Europe and almost non-existent communications and emergency response infrastructure along the North American coastline (Valsson and Ulfarsson, 2011; Dawson *et al.*, 2014). All these could reduce the appeal of using Arctic shipping routes rather than the Suez or Panama canals, especially after recent drop in oil prices reducing actual cost saving (Peters *et al.*, 2011).

The **Arctic fishing and aquaculture industry** would benefit from increased stock levels. Southern and pseudo-oceanic temperate fish species stocks are relocating North (Barents and Bering Seas), which could lead to unprecedented harvest levels most likely benefiting commercial fisheries (Hunt Jr. *et al.*, 2013; Christiansen *et al.*, 2014; Falk-Petersen *et al.*, 2015). The Barents Sea already displays higher levels of fish biomass density, with productivity at all trophic levels increasing with climate change and increased upwelling of nutrient-rich waters such as that of winter 2012. Actual streams of economic benefits depend on successfully avoiding overfishing under yet insufficient Arctic fisheries biological data (Christiansen *et al.*, 2014). Economic benefits are to be traded off with the negative impact of climate change and ocean acidification over calcareous shellfish (e.g. clams and oysters) and zooplankton (krill, pteropods consumed by salmons) (Ocean and Climate, 2015). It has been suggested that climate change could be directly or indirectly one of the causes of the disappearance of commercial species such as King Salmon off the coast of Alaska (Conley *et al.*, 2013). Climate change can negatively impact subsistence fishing in areas where it constitutes a major livelihood source (Himes-Cornell and Kasperski, 2015). Actual cost saving because of higher fish stocks needs to be traded off with the higher fuel costs in addition to those generally applicable to navigating the Arctic, and the high monitoring and enforcement costs to mitigate illegal, unreported, and unregulated (IUU) fishing in the Arctic (WWF, 2008).

The **oil and gas industry** would benefit from increased physical access to oil and gas resources including offshore reserves in the Chukchi Sea. 400 oil and gas onshore fields north of the Arctic Circle already account for approximately 240 billion barrels (BBOE) of oil and oil-equivalent natural gas - almost 10 percent of the world's known conventional resources (cumulative production and remaining proved reserves) (Bird *et al.*, 2008). The total undiscovered conventional oil and gas resources of the Arctic believed to be recoverable using existing technology are estimated to be approximately 90 billion barrels of oil, 1,669 trillion cubic feet of natural gas, and 44 billion barrels of natural gas liquids, with approximately 84% of the undiscovered oil and gas occurring offshore (Bird *et al.*, 2008). Oil and gas exploitation in the Arctic however comes with high costs for Arctic resistant infrastructure and operations, as well as capital costs for purchase of exploration licenses, leases, drilling permits, equipment and personnel (Conley *et al.*, 2013). There is still low competition from alternative energies - which have longer term potential - such as wind, waves, hydropower from the huge rivers that flow into the Arctic Ocean, and geothermal energy in a few places (Valsson and Ulfarsson, 2011). Following a report by Lloyd's, a large UK-based insurance market, and Chatham House, a British think tank, in April 2012, not all insurers are happy to insure operations in the Arctic (e.g., German bank West LB), partly in relation to the logistical and operational challenges due to the harsh and unpredictable Arctic conditions (Conley *et al.*, 2013). The recent drop in oil prices, combined with the exploitation of previously non-commercial natural reserves (e.g., shale and other unconventional gas) have generally reduced incentives to operate in the Arctic (Conley *et al.*, 2013).

The Dutch company Shell has pioneered efforts for offshore exploitation of oil and gas reserves in the Beaufort and Chukchi seas. The total investment cost for such operation is estimated to over US $4.5 billion for lease acquisition in 2005 and 2008, one sixth of its annual capital spending budget (Conley *et al.*, 2013). Total investment may exceed US $40-50 billion, which represents a significant financial risk for the company (Conley *et al.*, 2013).

The **mineral industry** would benefit from increased physical access to mineral resources such as lead and zinc in Alaska, gold in Canada, rare earth elements in Greenland, diamonds and iron in Canada and Greenland, aluminium in Iceland, and nickel in Russia (Duhaime and Caron, 2006; Conley *et al.*, 2013). In particular, Greenland could become a gateway for China's commercial entry into the Arctic region following recent discovery of large reserves of rare earth metals and increased Chinese strategic interest in these resources (Gattolin, 2014, Conley *et al.*, 2013). The GFMS index for base metals has increased by 300% between June 2002 and June 2007 (Gattolin, 2014, Conley *et al.*, 2013) whilst gold extraction has been put on hold in Alaska following low world market prices (Conley *et al.*, 2013). Mineral exploitation in the Arctic comes at high infrastructure and operation costs to withstand the harsh weather conditions. Infrastructure development and maintenance (road or rail corridors) is often borne by government rather than industry. Infrastructure development could unlock exploitation of resources (e.g. copper exploitation on hold in Alaska for lack of infrastructure, Conley *et al.*, 2013).

Climate change in the Arctic seems to have extended access to areas of touristic value, benefiting the **Arctic tourism industry** directly. It has opened up previously inaccessible areas for exploration and use by the expedition cruise ship industry as well as lengthened the shipping season (Dawson *et al.*, 2014). There is globally increasing demand for 'remote' tourism experiences and for the unique and iconic landscapes and wildlife which have led to an increase in Arctic tourism (Dawson *et al.*, 2014). Itineraries around Arctic Canada have more than doubled from 2005 to 2013, even if they remain limited with less than 30 itineraries a year (Dawson *et al.*, 2014). Infrastructure and operation costs for Arctic tourism operators are decreasing with climate change (Dawson *et al.*, 2014). Transaction costs are however high for tourism in Arctic areas, with operation permits difficult to obtain in some countries or associated with a high opportunity cost for the country because of tax avoidance and lack of effective communication between government agencies (Dawson *et al.*, 2014). Information costs can be high for navigation in 'unchartered' 'wild' Arctic areas, with navigation accidents such as the grounding of the Clipper Adventurer in the summer of 2010 occurring because of the poor accuracy of nautical maps (Dawson *et al.*, 2014).

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

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

ENVIRONMENTAL CONCERNS

The main environmental concerns are linked to the loss of pristine environment and unique Arctic ecosystems because of climate change or Arctic economic development pressures. In the USA, the Alaska National Interest Lands Conservation Act established in 1980 the Arctic National Wildlife Refuge (ANWR), a 19 million acre protected wilderness area including caribou herds, polar bears, and mammals as well as numerous fish and bird species.

Arctic economic development is associated with a high risk of air and marine pollution, particularly from oil spills, Persistent Organic Pollutants (POPs), heavy metals, radioactive substances, as well as the depletion of the ozone layer (Kao *et al.*, 2012; Conley *et al.*, 2013). Shell's operations in the Arctic have been slowed down following its oil spill barge, the Arctic Challenger, being damaged and lack of appropriate oil spill response measures in place (Conley *et al.*, 2013). Pollution generated by heavy diesel fuels of Arctic sea transport and tourism ships is a concern because of the accelerated sea ice decline it induces (Conley *et al.*, 2013). Concerns over pollution generated from mineral extraction have stalled mineral extraction for gold in Alaska (Conley *et al.*, 2013). The high risk of oil spill and reputational damage this could cause, insurers 'cold feet' to cover oil extraction in the Arctic combined with the high financial costs and risks have led to Total and BP to back off from the Arctic (Conley *et al.*, 2013).

Climate change externalities are a concern, as carbon emissions are more damaging in the Arctic than elsewhere (Whiteman *et al.*, 2013). Whiteman *et al.* (2013) estimated that methane released only from Arctic offshore permafrost thawing would have a price tag of USD 60 trillion in the absence of mitigating action, representing about 15% of the mean total predicted cost of climate-change impacts of USD 400 trillion. Mitigation could potentially halve the costs of methane releases (Whiteman *et al.*, 2013). Economic consequences are global, but with about 80% of them impacting the poorer economies of Africa, Asia and South America with increased frequency of extreme climate events (Whiteman *et al.*, 2013).

SOCIAL CONCERNS

Social concerns arise with climate change itself or with economic development and industrialisation. Most of the focus is on indigenous and resident populations of the Arctic who heavily depend on subsistence resources provided by their environment. The receding ice sheet and unstable ice pack because of climate change reduces game and sea mammal subsistence hunting and ice fishing opportunities (Ahlenius *et al.*, 2005 p.4; Himes-Cornell and Kasperski, 2015). Economic development generated increased competition for access to resources within and between industries. There is increased competition for fishing resources between coastal trawl and subsistence fishers in southern-based fisheries (Ahlenius *et al.*, 2005 p24). There is competition between subsistence fishing and offshore oil and gas extraction (Alaska) and between subsistence herders and oil and gas extraction (Russia) (Conley *et al.*, 2013; Duhaime and Caron, 2006)

Increased Arctic tourism is approved by indigenous and resident populations so long as it is managed well and respects sensitive and culturally important shore locations, wildlife and other natural landscapes (Dawson *et al.*, 2014). This has occurred de facto in Arctic Canada following 'good will' and high ethical standards of expedition cruise operators, but may be prone to change with new comers entering the industry because of a lack of formal regulation. Health risk concerns from indigenous population have in some cases stalled mineral extraction (e.g., uranium in Alaska, Conley *et al.*, 2013). Mineral extraction has been stalled in a few Alaska locations following strong indigenous concerns and contestation (e.g., gold and coal, Conley *et al.*, 2013).

As illustrated by historical changes in Russian governance, heavy dependence of Arctic communities on only one industry (service) makes Arctic population vulnerable to industry and government withdrawals with dire social consequences in an environment where employment alternatives are extremely limited (Amundsen, 2012; Glomsrød and Aslaksen, 2009).

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

Industries in the Arctic could potentially reap very high economic rewards from operating there, but the overall high investment and operation costs make it a financially high-risk environment to operate in and reduce its competitiveness compared to other regions of the world. All stakeholders seem to act to position themselves in the starting blocks by strategically securing access rights to Arctic resources and circumpolar routes. The 'cold rush' has not really started yet, with all stakeholders exercising relative caution in relation to the huge financial, reputational and political risks involved with economic development of the Arctic.

POLITICAL CHALLENGES AHEAD: RECONCILING DIFFERENT PERSPECTIVES TO MAKE THE MOST OF NEW OPPORTUNITIES AND INCLUDING ENVIRONMENTAL AND SOCIAL CONCERNS IN THE ARCTIC

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

One possible way to achieve this would be through integration of science, economics and diplomacy for conflict resolution (Berkman and Young, 2009). Science can provide a 'neutral' and recognised basis for establishing trust, monitoring, reporting and verification between all parties. Economics can provide assessment tools that consider trade-offs and resource use conflicts. Integration of science, economics and diplomacy could help bring together globally well-connected climate change winners in the Arctic and local and global losers. In turn, this could lead to realise economic opportunities arising with climate change in the Arctic while taking environmental and social concerns into account. The exact pathway to realise this will most likely vary within countries, between countries and between the local and the global levels, with the choice and choice processes for such pathway the responsibility of local and national decision-makers.

Within countries, economic and human development can be identified along three models: the 'North American model' which is a neo-liberal regime at the last frontiers (highly concentrated around extraction of non renewable rehouses), the 'Scandinavian model' which follows the redistribution mode of Northern Europe, and the 'Russian model' which is heavily shaped by its history (Glomsrød and Aslaksen, 2009). New institutional approaches for improved natural resource management have been explored in some Arctic areas with promotion of co-management and joint stewardship. This restructuring of power and responsibilities among stakeholders requires political will to move to decentralisation and collaborative decision-making with improved coordination between indigenous populations and government (Glomsrød and Aslaksen, 2009). Policies for promotion of external interests in the Arctic that recognise local populations as well as improved data over economic activities and distribution of benefits, social and environmental indicators have the potential to help minimise conflicts between stakeholders (Ahlenius *et al.*, 2005). Some Arctic countries have adopted measures for prevention of pollution with associated legally recognised compensation mechanisms, and established national strategies for adaptation to climate change and energy security (Ahlenius *et al.*, 2005; Amundsen *et al.*, 2007). For instance, Canada is extending the reach of its Arctic Waters Pollution Prevention Act (Berkman and Young, 2009). Some Arctic countries have set up national research programmes with an objective to inform action in the Arctic for adaptation under climate change (The Arctic – The Canary in the Mine. Global implications of Arctic climate change. Norwegian-French conference in Paris, 17 March 2015). Such national initiatives, however, do not allow to resolve transboundary issues with a need for supra-national approaches (Berkman and Young, 2009).

Between countries, there are a number of jurisdictional conflicts (Figure 5), increasingly severe clashes over the extraction of natural resources and trans boundary security risks, and the emergence of a new 'great game' among the global powers with global security implications (Berkman and Young, 2009). Regional and international cooperation seems to be generally favoured in spite of demonstrations of unilateral sovereignty extensions in disputed or international areas (flag planted by Russia under the North pole, unilateral extensions of Iceland fishing quotas, Northern Sea Route and Northwest Passage disputed sovereignty statuses).

Few but important binding international agreements apply to the Arctic. The United Nations Convention on the Law of the Sea, UNCLOS, of 10 December 1982 is considered one of the main binding agreements providing a legal framework for use of the Arctic to this day. UNCLOS helps regulate access to Arctic resources, maritime traffic and pollution through clear identification of national jurisdictions and provision of a mechanism for dispute resolution (Berkman and Young, 2009). In addition to the UNCLOS, there are a number of other international conventions that are relevant for Arctic (Dawson *et al.*, 2014): the International Convention for Safety of Life at Sea (SOLAS) which focuses on safety requirements, the International Convention for the Prevention of Pollution from Ships (MARPOL) which focuses on environmental protection, the Convention on Standards of Training of Seafarers (STCW) which focuses on training and competency, and The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) which applies to part of the Arctic and provides a guide for international cooperation on the

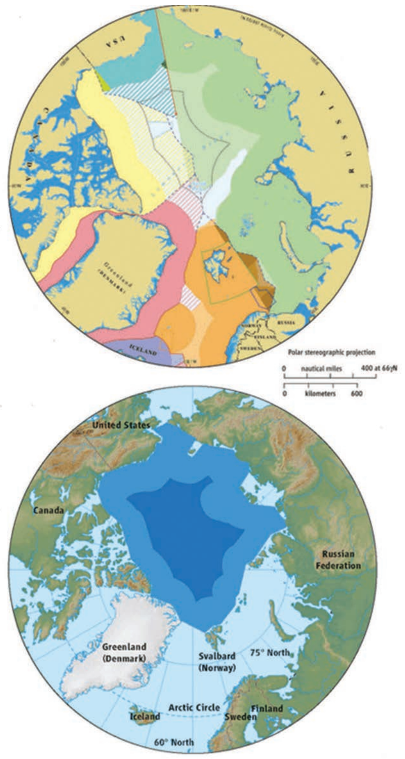

Fig.5 — Arctic sea ice Jurisdictional representations of the Arctic Ocean with boundaries based on (top) sea floor as a source of conflict among nations (different colours) and (bottom) overlying water column as a source of cooperation, with the high seas (dark blue) as an international space in the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

protection of the marine environment of the North-East Atlantic.

More recently, a number of framework agreements have been established, in particular in relation to shipping in the Arctic, search and rescue operations and pollution management. They provide some guidance and structure for international cooperation in the Arctic. The International Maritime Organization (IMO) has been promoting adoption of a series of voluntary guidelines such as those 'for Ships Operating in Ice-Covered Arctic Waters' in 2002, 'on voyage planning for passenger ships operating in remote areas', and 'for passenger ships operating in areas remote from SAR facilities' (Berkman and Young, 2009). The IMO has more recently adopted in 2014 an International Code for Ships Operating in Polar Waters (or 'Polar Code'). The Polar Code will be made mandatory under the International Convention for the Safety of Life at Sea (SOLAS) from 2017, There are current discussions to make the Polar Code compulsory under the International Convention for the Prevention of Pollution from Ships (MARPOL).

All these agreements have been possible thanks to the work of intergovernmental organisations such as the United Nations and its agencies (e.g., International Maritime Organization), and international fora such as the Arctic Council. Such organisations and fora provide platforms for dialogue between countries and have successfully led to the establishment of concerted and mutually agreed 'win-win' coordinated and concerted action. The Arctic Council is formed by 8 states with land within the Arctic Circle: the United States of America (Alaska), Canada, Denmark (Greenland and the Faroe Islands), Iceland, Norway, Sweden, Finland, and the Russian Federation. The Council is a high level intergovernmental forum for Arctic governments and peoples (http://www.arctic-council.org). It is the main institution of the Arctic and was formally established by the Ottawa Declaration of 1996 to provide a means for promoting cooperation, coordination and interaction among the Arctic States, with the involvement of the Arctic Indigenous communities and other Arctic inhabitants on common Arctic issues, in particular issues of sustainable development and environmental protection in the Arctic. The Council has no regulatory authority but has facilitated the production of scientific assessments such as the Arctic Climate Impact Assessment (ACIA) by its Arctic Monitoring and Assessment Programme (AMAP) working group, Conservation of Arctic Flora and Fauna (CAFF) working group, along with the International Arctic Science Committee (IASC). The Council has successfully brought Arctic issues to the attention of global fora, with the 2001 Stockholm Convention on Persistent Organic Pollutants in part informed thanks to the work of the Arctic Council (Berkman and Young, 2009).

There are a number of international scientific monitoring and research bodies leading scientific initiatives and projects, in the Arctic. Such international collaborative scientific projects could provide a basis to build trust and enhance Arctic state cooperation through establishing scientifically sound common baselines (Berkman and Young, 2009). These include (but are not limited to) the International Arctic Science Committee, the European Polar Board, the French Arctic Initiative (`Chantier Arctique français').

There is real potential to harness and develop existing institutions (*i.e.* organisations, binding and non binding agreements) and build up existing institutional capacity. The pace of economic development will be extremely fast when the cold rush starts. Current economic development is already creating new institutional needs in the Arctic. One of the challenges will be to build up existing capacity fast enough to keep up with the pace of economic development. There is certainly strong potential for creating shared economic wealth and well-being. Actual choices made by Arctic industries and countries for economic development, coordination and cooperation within the coming years will shape what the future Arctic will look like.

REFERENCES

- AHLENIUS H., JOHNSEN, K. and NELLEMANN, C., 2005 – *Vital Arctic Graphics - People and global heritage on our last wildshores.* UNEP/GRID-Arendal, www. grida. no/files/publications/vitalarcticgraphics. pdf.
- AMUNDSEN H., 2012 – *Illusions of Resilience? An Analysis of Community Responses to Change in Northern Norway.* Ecology and Society, 17 (4): 46.
- AMUNDSEN H., HOVELSRUD G. K. and PRESTRUD P., 2007 – *Workshop Report of the Workshop on Adaptation to Climate Change in the Arctic, 26-27 June 2006 Oslo, Norway.* Hosted by the Ministry of ForeignAffairs, Norway. Organised by CICERO – Centre for International Climate and Environmental Research – Oslo, www.cicero.uio.no/workshops/acia-workshop-2006/Workshop-report-Final.pdf, 62 p.
- ARCTIC. RU, 2015 – *Structure of the Economy.* http://Arctic.ru/economy-infrastructure/structure-economy.
- BERKMAN P. A. and YOUNG O. R., 2009 – *Governance and Environmental Change in the Arctic Ocean.* Science. 324: 339-340.
- BIRD K., CHARPENTIER R., GAUTIER D., HOUSEKNECHT D., KLETT T., PITMAN J., MOORE T. E., SCHENK C. J., TENNYSON M. E. and WANDREY C. J., 2008 – *Circum-Arctic Resource Appraisal; Estimates of Undiscovered Oil and Gas North of the Arctic Circle.* U. S. Geological Survey, USGS Fact Sheet 2008-3049, http://pubs.usgs. gov/fs/2008/3049.
- BOÉ J., HALL A. and QU X., 2009 – *September Sea-Ice Cover in the Arctic Ocean Projected to Vanish by 2100.* Nature Geoscience, 2: 341-343.
- CHRISTIANSEN J. S., MECKLENBURG C. W. and KARAMUSHKO O. V., 2014 – *Arctic Marine Fishes and their Fisheries in Light of Global Change.* Global Change Biology, 20: 352-359.
- CONLEY H. A., PUMPHREY, D. L., TOLAND, T. M. and DAVID, M., 2013 – *Arctic Economics in the 21st Century: The Benefits and Costs of Cold. A Report of the CSIS Europe Program.* Center for Strategic and International Studies. http://csis.org/files/publication/130710_Conley_ArcticEconomics_WEB.pdf.
- DAWSON J., JOHNSTON M. E. and STEWART, E. J., 2014 – *Governance of Arctic Expedition Cruises Hips in a Time of Rapid Environmental and Economic Change.* Ocean & Coastal Management, 89: 88 – 99.
- DITTMER J., MOISIO S., INGRAMA A. and DODDS K., 2011 – *Have you Heard the One about the Disappearing Ice? Recasting Arctic Geopolitics.* Political Geography, 30: 202 – 214.
- DUHAIME G. and CARON A., 2006 – *The Economy of the Circumpolar Arctic.* In *The Economy of the North,* GLOMSRØD S. and ASLAKSEN I. (eds), 17-23.
- FALK-PETERSEN S., PAVLOV V., BERGE J., COTTIER F., KOVACS K. and LYDERSEN C., 2015 – *At the Rainbow's end: High Productivity Fueled by Winter upwelling along an Arctic Shelf.* Polar Biology, 38: 5-11.
- GATTOLIN A., 2014 – *Rapport d'information fait au nom de la commission des affaires européennes sur les stratégies européennes pour l'Arctique.* Enregistré à la Présidence du Sénat le 2 juillet 2014, Les Rapports du Sénat no 634, http://www.senat. fr/rap/r13-684/r13-684.html, 190 p.

- GLOMSRØD S. and ASLAKSEN I., 2009 – *The Economy of the North 2008.* Statistics Norway. http://ssb.no/a/english/publikasjoner/pdf/sa112_en/sa112_en.pdf, 102 p.
- HIMES-CORNELL A. and KASPERSKI S., 2015 – *Assessing Climate Change Vulnerability in Alaska's Fishing Communities.* Fisheries Research, 162 : 1 – 11.
- HUNT Jr G. L., BLANCHARD A. L., BOVENG P., DALPADADO P., DRINKWATER K. F., EISNER L., HOPCROFT R. R., KOVACS K. M., NORCROSS B. L., RENAUD P., REIGSTAD M., RENNER M., SKJOLDAL H. R., WHITEHOUSE A. and WOODGATE R. A., 2013 – *The Barents and Chukchi Seas : Comparison of two Arctic Shelf Ecosystems.* Journal of Marine Systems : Large-scale Regional Comparisons of Marine Biogeochemistry and Ecosystem Processes - Research Approaches and Results. 109 – 110 : 43-68.
- KAO S. -M., PEARRE N. S. and FIRESTONE J., 2012 – *Adoption of the Arctic Search and Rescue Agreement : a Shift of the Arctic Regime Toward a Hard Law Basis ?* Marine Policy, 36 : 832 – 838.
- KWOK R. and ROTHROCK D. A., 2009 – *Decline in Arctic Sea Ice Thickness from Submarine and ICES at Records : 1958-2008.* Geophysical Research Letters, 36 : L15501.
- L'ARCTIQUE – *Sentinelle avancée du réchauffement climatique.* Journée-débats co-organisée par la France et la Norvège, Paris, 17 mars 2015.
- LIU M. and KRONBAK J., 2010 – *The Potential Economic Viability of Using the Northern Sea Route (NSR) as an Alternative Route between Asia and Europe.* Journal of Transport Geography, 18 : 434 – 444.
- MAGDANZ J. S., TAHBONE S., AHMASUK A., KOSTER D. S. and DAVIS B. L., 2007 – *Customary Trade and Barter in Fish in the Seward Peninsula Area : FIS Project 04-151.* TechnicalPaper No. 328. Division of Subsistence, Alaska Department of Fish and Game, Juneau, Alaska, Department of Natural Resources, Kawerak, Inc., Nome, Alaska, www.subsistence.adfg.state.ak.us/TechPap/tp328. pdf.
- MINISTÈRE DES AFFAIRES ETRANGÈRES DE NORVÈGE, 2015 – *Le monde du grand nord. La création de valeurs et les ressources. Changements climatiques et connaissances. Le développement des régions du Grand Nord nous concerne tous.* www. norvege. no/PageFiles/732027/Le_Monde_du_Grand_Nord_2015. pdf, 20 p.
- PARKINSON C. L., 2014 – *Global Sea Ice Coverage from Satellite Data : Annual Cycle and 35-Yr Trends.* J. Climate, 27 : 9377 – 9382.
- PETERS G. P., NILSSEN T. B., LINDHOLT L., EIDE M. S., GLOMSRØD S., EIDE L. I. and FUGLESTVEDT J. S., 2015 – *Future Emissions from Shipping and Petroleum Activities in the Arctic.* Atmospheric Chemistry and Physics, 11 : 5305-5320.
- PLATEFORME OCÉAN ET CLIMAT, 2015 – *Fiches scientifiques.* www. ocean-climate. org, 69 p.
- SERREZE C. M., HOLLAND M. M. and STROEVE J., 2007 – *Perspectives on the Arctic's Shrinking Sea-Ice Cover.* Science, 315 : 1533-1536.
- US NATIONAL SNOW AND ICE DATA CENTER IN BOULDER COLORADO, 2015 – *Climate Change in the Arctic.* https ://nsidc.org/cryosphere/arctic-meteorology/climate_change.html.
- VALSSON T. and ULFARSSON G. F., 2011 – *Future Changes in Activity Structures of the Globe under a Receding Arctic Ice Scenario.* Futures, 43 : 450 – 459.
- WHITEMAN G., HOPE C. and WADHAMS P., 2013 – *Climate science : Vastcosts of Arctic change.* Nature, 499 : 401-403.
- WWF, 2008 – *Illegal Fishing in Arctic Waters.* Oslo : WWF International Arctic Programme. http ://assets.panda.org/downloads/iuu_report_version_1_3_30apr08.pdf.

Ocean, Biodiversity and Climate

Gilles Bœuf

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).

1 Practical salinity unit

Oxygen then began diffusing beyond of the aquatic environment: the composition of today's atmosphere – with 21% oxygen – dates from the Cretaceous, around 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.
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 (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!

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Ecosystem Services and Marine Conservation

Marine and land ecosystems provide many benefits to society. Marine ecosystems are under increased pressure because of climate change, expanding human populations and needs. Increased pressures and associated impacts on ecosystems often render current management and conservation policies inappropriate to mitigate or regulate such pressures and maintain the level of ecosystem benefits provided. Integrated approaches centred on ecosystems can help assess synergies and trade offs for delivery of benefits provided by ecosystems for management options with different levels of usage and conservation. The ecosystem service framework can help structure the production of comprehensive assessments drawing from multi-disciplinary academic knowledge and management experience. Interaction and dialogue with stakeholders structured by a step-wise iterative 'triage' process can help ensure ecosystem assessment outputs are meaningful, salient (reflecting the interests of those involved), useful to management and policy concerns, needs and projects, and feasible under available knowledge and resources. The ecosystem service framework needs to be applied at regular intervals to gain an idea of how the benefits derived from ecosystems evolve in time. Using the ecosystem service framework in combination with the DPSIR framework to identify Drivers, Pressures, States, Impact, Response can provide very rich insights to discussions for establishment of management plans and policies for marine conservation, especially those aiming to mitigate or adapt to climate change pressure, for delivery of healthy ecosystems and associated human well-being.

Healthy marine and land ecosystems provide a wide range of benefits to society such as food, materials, recreation, carbon regulation etc. Marine ecosystems are changing fast under increased and increasing pressures and impacts from climate change and increasing human populations with expanding needs. Sea level rise, ocean acidification, eutrophication, change in water temperature and coastal weather patterns directly impact, often negatively, wild fish stocks and aquaculture production, coastal infrastructures generating maintenance, and recreational activities (Ocean and Climate, 2015). Expanding needs of increasing human populations is one of the drivers of unsustainable levels of exploitation of marine ecosystems, and their many fish stock overfished. The ocean supports increasingly diverse needs, with competition for access to marine resources and use of the marine space for recreation and tourism, shipping, deep sea mining, renewable marine energies (e.g., offshore wind turbines), in addition to subsistence and commercial fishing, The benefits provided by marine ecosystems are shrinking fast in places under such pressures.

Management decisions and ecosystem conservation policies are very often not designed in a flexible enough way to allow for appropriate adaptation to changing circumstances such as changing ecosystems, pressures, and human needs and impacts. Changing pressures and needs consequently render current management and conservation policies inappropriate to effectively mitigate or regulate such pressures and maintain the level of benefits provided by healthy ecosystems. Tensions and conflicts arising between ecosystem users are generally more acute for higher levels of competition to satisfy human needs and impacts. They can be exacerbated by inappropriate management decisions and policies. Management decisions and policies, on the other hand, have the potential to conciliate tensions and conflicts to certain extent. Management decisions and policies are social constructs that not only influence tensions and conflicts but their design is also influenced by such tensions and conflicts.

Healthy ecosystems are often a necessary condition to achieving sustainable development, *i.e.* "development that meets the needs of present generations without compromising the ability of future generations to meet their own needs" (Bruntland, 1987). The challenge we are facing now is to ensure conservation of healthy marine ecosystems in a highly dynamic environment so as to meet future as well as current needs. Establishment of marine protected areas is one possible option to help protect rich and healthy ecosystems, which could be complemented by other instruments to effectively mitigate drivers and pressures. 'Blue growth' and the 'blue economy' - mirroring 'green growth' and the 'green economy' - are seen as possible ways to foster sustainable development of human activities related to the marine environment. 'Blue businesses' have the potential to advance human well-being with job and value-added creation, and investment into maintaining healthy marine ecosystems or restoring degraded marine ecosystems. The concept of 'blue economy' goes beyond the value creation by businesses (blue growth) to include non market benefits derived from recreation in marine ecosystems, from bequeathing healthy marine ecosystems to our children for their own enjoyment, or simply from knowing that healthy marine ecosystems simply exist.

A range of scientific methods and approaches has been established in the literature to help assess different management options and provide a basis for managers and policy-makers to make informed decisions. Operational application of such methods and approaches for marine ecosystem can be based on a common ecosystem approach for establishment of structured ecosystem assessment outputs using the comprehensive ecosystem service framework. A 'triage process' structuring interaction and dialogue between researchers and managers can ensure provision of information pertinent to decisions involving trade offs between ecosystems and human needs or between different types of human needs.

ECOSYSTEM APPROACH FOR CROSS-SECTORAL ASSESSMENT OF ECOSYSTEMS

The ecosystem approach has become very popular over the past decade as a harmonised way to conceptualise management problems that involve natural ecosystems. The International Council for the Exploration of the Sea (ICES) defines the ecosystem approach for application to marine ecosystems as "the **comprehensive integrated management of human activities** based on best available scientific knowledge about the ecosystem and its dynamics, in order to **identify and take action on influences which are critical to the health of the marine ecosystems**, thereby **achieving sustainable use** of ecosystem goods and services and **maintenance of ecosystem integrity**" (ICES, 2005, emphasis added). Previous management approaches were mostly sectoral with human activities considered independently. Such sectoral approaches however proved inappropriate when dealing with global cross-sector phenomena such as climate change and fail to capture trade offs between different human activities competing for resources from or access to the same ecosystem. The ecosystem approach considers together ecosystems and the associated human activities and trade offs, and is therefore suited to comprehensive integrated assessment of ecosystems for different management and policy options for input into decision-making processes.

The ecosystem approach was first elaborated by ecologists concerned by critical environmental problems and was formalised in the 1970s for the purpose of political advising (Mongruel and Beaumont, 2015). It is established at the junction of ecology and economics with human activities linked to 'energy flows' within and between ecosystems (thermodynamics). The ecosystem approach is at the heart of a relatively recent sub-branch of economics, ecological economics, which conceptualises the economy as a sub-component of ecosystems, in contrast to previous economic conceptualisations (Biely, 2014). Natural scientists and economists have joined their efforts in order to estimate the (socio-economic) "value" of ecosystems (Gómez-Baggethun *et al.*, 2010). The most representative example of such collaboration is possibly the paper entitled "The value of the world's ecosystem services and natural capital" (Costanza *et al.*, 1997). Estimates of socio-economic values of several ecosystems have been recently updated (Costanza *et al.*, 2014). The estimated value of marine ecosystems, inclusive of open oceans and coastal areas, is USD 796/ha/yr[1] in 1997 and USD 1,368/ha/yr in 2011 (Costanza *et al.*, 2014). Total socio-economic value of marine ecosystems is estimated to USD 49.7 trillion/yr in 2011, *i.e.* about 2/3 of the global gross national product (around USD 75.2 trillion/yr).

Such global studies and numbers have had a great role and impact for raising awareness of decision-makers and policy-makers of the need to include non-market benefits of ecosystems and adopt a broader perspective than short-term financial interests. Such non-market benefits include the value societies allocate to knowing healthy ecosystems exist (existence value), to bequeathing healthy ecosystems to future generations (bequest value) or to good 'stewardship' of ecosystems (stewardship value). This forms part of what economists call the '**Total Economic Value**" which encompasses both market and non-market components to capture the 'true' value of ecosystems to society through increased welfare and not just increased profits.

Estimation of such 'inclusive' numbers through economic valuation methods, however, tends to be highly time- and effort-consuming and requires a lot of specific skills and capacity. Such 'global' numbers aggregate a lot of different elements together using money as a 'common measuring rod'. This limits their ability to inform management actions, especially at the more local level where finer detail is often needed than one single number. Depending on the specific context, alternative more flexible methods may be more suited for local-level assessment. For example, multi-criteria analysis allows for combination of quantitative and qualitative information, measured in monetary values and physical units, over a range of different academic disciplines and 'on-the-ground' experience. Such a method can be used as a way to integrate different kinds of knowledge and usually matches well the way people themselves integrate knowledge and take decisions.

THE ECOSYSTEM SERVICE FRAMEWORK AS A COMPREHENSIVE 'COMMON LANGUAGE' TO STRUCTURE ECOSYSTEM ASSESSMENTS

The ecosystem approach is associated with an operational framework, the ecosystem service framework. The framework was popularised and formally established within the decision-making sphere by the Millennium Ecosystem Assessment (2005). The framework provides a non-

1 All numbers from Costanza *et al.* (2014) are expressed in 2007 USD.

Operationalising the ecosystem service framework and 'triage process': VALMER project as an example

(adapted from Mongruel and Beaumont, 2015)

"The VALMER framework for the operational assessment of marine and coastal ecosystem services provides a structure to guide practitioners in undertaking comprehensive, transparent and appropriate marine ecosystem services assessments. It does not, however, provide a set of rigid and prescriptive rules that are applicable in their entirety to all circumstances. Marine ecosystem service assessments are context dependent, as the needs of managers and stakeholders, the services about which they are concerned, and the resources available for the assessment are highly variable. This necessitates a flexible guidance framework."

Table 1 details some of the ecosystem services that were identified as part of the project to facilitate their assessment and valuation in economic terms. Table 2 shows an example of assessment based on expert opinion structured along different ecosystem services.

	Marine Ecosystem Services	Specific components
Specific components	Food provision	Fisheries and aquaculture
	Water storage and provision	Industrial use of sea water
	Biotic materials and biofuels	Medicinal sector Energy resources 'Ornamental resources
Regulation and maintenance services	Water purification	Treatment of human waste
	Air quality regulation	Absorption of pollutant
	Coastal protection	Natural defence
	Climate regulation	Carbon sequestration
	Weather regulation	*No example found*
	Ocean nourishment	Nutrient and organic matters
	Life cycle maintenance	Maintenance of habitats
	Biological regulation	*No example found*
Cultural services	Symbolic and aesthetic values	Heritage Aesthetic value
	Recreation and tourism	Recreational activities (non market activities) Recreational fishing Tourism industry (market activities)
	Cognitive effects (education and research)	

Table 1 — Marine ecosystem assessment (adapted from Mongruel and Beaumont, 2015, Table 6 pages 17-18).

	Likely use of value in policy decisions	Potential vor falue to change	Influence of external factors	Feasibility
Saltmarsh creation	High	Medium	Medium	High
Water quality	Low	Low	Medium	High
Fish habitat	High	High	Medium	High
Disturbance	Medium	Low	Low	Medium
Atlantic Array	Medium	High	High	Medium

High Medium Low

Table 2 — Scores in each category (last 4 columns) for the shortlisted management concerns (first column) based on expert opinion (Mongruel and Beaumont, 2015, Table 8, page 32).

prescriptive basis to establish a comprehensive ecosystem assessment based on the services ecosystems provide. It divides ecosystem services into four mutually exclusive categories: provisioning services, regulating services, cultural services and supporting services. **Provisioning** services refer to the provision by ecosystems of food, water, fibre, timber, fuel, minerals, building materials and shelter, and biodiversity and genetic resources for medicines or food additives. **Regulating** services refer to the benefits derived from regulation of processes such as climatic events (storm protection), carbon storage and sequestration, water flows (floods and droughts), water purification, pollution and waste treatment, soil erosion, nutrient cycling, regulation of human diseases, and biological control. **Cultural** services include aesthetic, spiritual, educational, and recreational aspects and are mainly experienced through tourism or religious practices. Supporting services include primary production, soil formation, and nutrient cycling. The first three types of services are more directly linked to financial flows. **Supporting** services tend to be captured in other ecosystem services (e.g., high fish stocks depend in part on good nutrient cycling). Contrary to the other types of services, supporting services are often not valued in economic terms when necessary for supply of other ecosystem services, which could lead to count the same economic value twice (as a supporting service, and as a part of another type of ecosystem service).

These ecosystem services collectively provide the basis of human well-being. As such, all these types of ecosystem services have an economic value, more or less well captured by market prices and considered with varying degrees in individual or collective decision-making processes. Such a framework helps identify services that are not – or not fully – valued in economic or social terms, which creates incentives for overexploitation or degradation of ecosystems.

Climate change affects the level and nature of provision of these ecosystem services, while regulating ecosystem services such as carbon storage and sequestration can help regulate climate variation. The ecosystem service frameworks allows for explicit trade offs between different processes underlying ecosystem services. Mangrove forests in a coastal ecosystem have been in some cases removed to allow for increased shrimp farming and production, at the cost of a lower level of protection against coastal erosion and extreme weather events, such as storm winds and floods, as well as tsunamis – *i.e.* an increase in provisioning service at the cost of a reduction in regulating service (Barbier and Cox, 2003).

The advantage of the ecosystem service framework is that it is comprehensive, generic and flexible enough for customisation to specific assessment contexts. The different categories of ecosystem services can easily be replaced by context-specific examples and vocabulary adapted to different audiences, especially those not used to working with the framework (Table 1). It is necessary to link identification of ecosystem services to ecosystems functions, building up from ecological knowledge and allowing integration of a social science perspective identifying well-being variations stemming from changes in the functioning or structure of ecosystems. The ecosystem service framework can provide a useful framework for researchers and practitioners to build up an ecosystem assessment. Such ecosystem assessment can be used as part of informed decision-making processes to balance ecosystem conservation with economic development according to society's preferences.

MAKING ECOSYSTEM ASSESSMENT MEANINGFUL, SALIENT, USEFUL, AND FEASIBLE USING A STEP-WISE ITERATIVE APPROACH OR 'TRIAGE PROCESS'

Assessment processes that involve stakeholders or decision-makers can help ensure ecosystem assessment is conducted so as to be meaningful, salient (reflecting the interests of those involved), useful to management and policy concerns, needs and projects, and feasible under available knowledge and resources, thereby ensuring output relevance to discussions around ecosystem management and policy. Involvement of decision-makers and stakeholders in ecosystem assessment processes tend to increase likelihood that the outputs from such assessments will be actually used.

There are several models for structuring ecosystem assessment processes, all built around the same three stages, with variations between models and their application stemming from the range of possible choices at each stage. A 'triage process' encompassing three transparent and successive stages has been developed to support operational marine management as part of the "Valuing ecosystem services in the western Channel (VALMER)" project funded by the European Union (http://www.valmer.eu) (Pendleton *et al.*, forthcoming):

i. idefining the aims and scope of the assessment, often overlooked, to ensure it is meaningful and salient;
ii. selecting the ecosystem services to be assessed based on three criteria (perceptions of current trends, influence of management intervention, and influence of other factors), with clear identification of synergies and trade-offs between ecosystem services provided, to ensure assessment is useful; and
iii. choosing the assessment method (e.g., measures of ecological output, economic impact, total economic value etc.). Because of the decomposition of an ecosystem into different ecosystem services, the ecosystem service framework can help at the third stage of the 'triage process' with different assessment methods used for different ecosystem services.

The 'triage process' takes a strategic decision-making approach with decisions at each stage made after discussions between researchers, decision-makers, practitioners and/or stakeholders. Its implementation can assist in identifying methodologies, scale and scope for co-construction of ecosystem assessment that is deemed relevant and appropriate.

The 'triage process' can be combined with the ecosystem service framework at each of the three stages. Such a 'triage process' for structuring assessment processes can be applied in a flexible and iterative way, sometimes requiring a highly skilled facilitator for the discussions. Such an approach allows for data gaps and uncertainty, which can be reduced through dialogue with stakeholders. Such an approach helps foster collaboration between scientists from different disciplinary background and identify the 'best expert for the job' depending on the issue at stake – ecologists having a greater weight in conducting the assessment when the issue is linked to supply of ecosystem services whereas social scientists stepping in mainly for issues linked to demand for ecosystem services.

CONCLUSION

Ecosystem service framework and 'triage process' can be combined for meaningful, salient, useful and feasible ecosystem assessment. Assessment format is adapted to needs from managers and decision-makers and integrates very different types of knowledge as well as knowledge from very different disciplines, reflecting the way managers and policy-makers function. Such knowledge-based integrated participatory ecosystem assessment requires a high level of collaboration between academic disciplines, especially environmental sciences and social sciences and building strong partnerships with managers and decision-makers.

The ecosystem service framework needs to be applied at regular intervals to gain an idea of how the benefits derived from ecosystems evolve in time. This goes back to the idea that we need iterative processes in line with a changing environment, changing drivers and changing pressures. Mitigation and regulation management and policies target drivers and pressures of change, which are not the specific focus of the ecosystem service framework. Using the ecosystem service framework and 'triage process' in combination with the DPSIR framework based on identification of Drivers, Pressures, States, Impact, Response and how they relate together can provide very rich insights to discussions. Iterative assessment capturing evolutions and changes can provide a basis to inform the establishment of new management plans and policies for marine conservation, or adaptation of current management practices and policies. Keeping management choices and policies flexible and allowing for integration of lessons learnt over time by design is key for successful delivery of healthy ecosystems and associated human well-being in a changing environment, and even more importantly at the global level under climate change.

REFERENCES

- BARBIER E. and COX M., 2003 – *Does Economic Development Lead to Mangrove Loss ? A Cross Country Analysis.* Contemporary economic policy, 21 (4), 418-432.
- BIELY, K., 2014 – *Environmental And Ecological Economics : Two Approaches in Dealing With Economy-Environment Interrelations and the Example of the Economics of Land Degradation Initiative.* Masters thesis. University of Vienna, http://ubdata.univie.ac.at/AC11451272, 272 pages.
- BRUNTLAND, G. (ed), 1987 – *Our Common Future.* Report of the World Commission on Environment and Development. Oxford, UK : Oxford University Press.
- COSTANZA R., D'ARGE R., de GROOT R., FARBER S., GRASSO M., HANNON B., LIMBURG K., NAEEM S., O'NEIL R., PARUELO J., RASKIN R., SUTTON P. and VAN DEN BELT M., 1997 – *The Value of the World's Ecosystem Services and Natural Capital,* Nature, 387, 253-260.
- COSTANZA R., de GROOT R., SUTTON P., VAN DER PLOEG S., ANDERSON S.J., KUBISZEWSKI I., FARBER S. and TURNER R.K., 2014 – *Changes in the Global Value of Ecosystem Services.* Global Environmental Change, 26 : 152-158.
- GÓMEZ-BAGGETHUN E., DE GROOT R., LOMAS P.L. and MONTES C., 2010 – *The History of Ecosystem Services in Economic Theory and Practice : from Early Notions to Markets and Payment Schemes.* Ecological Economics. 69 : 1209-1218.
- ICES, 2005 – *Guidance on the Application of the Ecosystem Approach to Management of Human Activities in the European Marine Environment.* ICES Cooperative Research Report no. 273, 22 pages.
- MILLENNIUM ECOSYSTEM ASSESSMENT, 2005 – *Ecosystems and Human Well-Being.* Geneva, Switzerland : World Health Organization.
- MONGRUEL R. and BEAUMONT N. (coordinators), 2015 – *A Framework for the Operational Assessment of Marine Ecosystem Services.* Contributors : HOOPER T. LEVREL H., SOMERFIELD P., THIÉBAUT É., LANGMEAD O. and CHARLES M., March 2015, www.valmer.eu/wp-content/uploads/2015/03/A-framework-for-the-operational-assessment-of-marine-ecosystem-services.pdf, 80 pages.
- OCÉAN ET CLIMAT, 2015 – *Fiches scientifiques.* www. ocean-climate. org.
- PENDLETON, L., MONGRUEL, R., BEAUMONT, N., HOOPER, T. and CHARLES, M. – *A Triage Approach to Improve the Relevance of Marine Ecosystem Services Assessments.* Marine Ecological Progress Series, forthcoming.

Coral Reefs and Climate Change

Denis Allemand

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 depends 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 impedes the formation of coral 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 skeletons 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 it is 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 known as the only animal construction visible from space. The second largest reef is French New Caledonia Barrier, which is 1600 km long. These two barrier reefs have been included in the UNESCO World Heritage list (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 extend to 1 km 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 approximatively 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 past belief, 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). By means of modern sequencing techniques, a large diversity in bacteria has been identified 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, 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 dispersal. 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

The word Coral entails a plurality of species belonging to the phylum of *Cnidaria* and forms the basis of several ecosystems:

- Cold-water corals, also called deep-sea corals: these corals belong to the same order of cnidarians as reef-building corals. 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, 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 m^2 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 a dozen species for an equivalent coastline.

This «biodiversity» is however not homogeneous between reefs. In fact, 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 food resources, coastal protection and tourism… Approximately 275 million people worldwide live within 30 km of a coral reef and the livelihood of over 500 million people directly depends on reefs. 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 km^2.
- 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) highlighted 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).

REFERENCES

- ALLEMAND D., FURLA P. and BÉNAZET-TAMBUTTÉ S., 1998 – *Mechanisms of Carbon Acquisition for Endosymbiont Photosynthesis in Anthozoa.* Can J Bot 76 : 925-941.
- ALLEMAND D., TAMBUTTÉ É., ZOCCOLA D. and TAMBUTTÉ S., 2011 – *Coral Calcification, Cells to Reefs.* In *Coral Reefs : an Ecosystem in Transition*. Springer Netherlands.
- BARNES D. J. and CHALKER B. E., 1990 – *Calcification and Photosynthesis in Reef-Building Corals and Algae*. In *Coral Reefs*. Amsterdam : Elsevier.
- BIGGS D., 2011 – *Understanding Resilience in a Vulnerable Industry : the Case of Reef Tourism in Australia.* Ecology and Society 16 (1) : 30.
- CAIRNS S. D., 1999 – *Species Richness of Recent Scleractinia.* Atoll Res Bull 459 : 1-46.
- CAR/ASP, 2003 – *Le coralligène en Méditerranée*. PNUE.
- CHEN P. Y., CHEN C. C., CHU L. and MCCARL B., 2015 – *Evaluating the Economic Damage of Climate Change on Global Coral Reefs.* Global Environmental Change 30 : 15-20.
- CONSERVATION INTERNATIONAL, 2008 – *Economic Values of Coral Reefs, Mangroves, and Seagrasses : a Global Compilation.* Center for Applied Biodiversity Science, Arlington.
- DARWIN C. R., 1842 – *The Structure and Distribution of Coral Reefs. Being the First Part of the Geology of the Voyage of the Beagle, under the Command of Capt. Fitzroy, R.N. during the Years 1832 to1836.* London : Smith Elder and Co.
- DE'ATH G., FABRICIUS K. E., SWEATMAN H. and PUOTINEN M., 2012 – *The 27-Year Decline of Coral Cover on the Great Barrier Reef and its Causes*. Proceedings of the National Academy of Sciences of the United States of America, 109 (44), 17995-17999.
- DONEY S. C., V. FABRY J., FEELY R. A. and KLEYPAS J. A., 2009 – *Ocean Acidification : the Other* CO_2 *Problem.* Ann Rev Marine Sci 1 : 169-192.
- DULLO W. C., 2005 – *Coral Growth and Reef Growth : a Brief Review*. Facies 51 : 33-48.
- EREZ J., REYNAUD S., SILVERMAN J., SCHNEIDER K. and ALLEMAND D., 2011 – *Coral Calcification under Ocean Acidification and Global Change*. In *Coral Reefs : an Ecosystem in Transition*. Springer Netherlands.
- FRANKIGNOULLE M. and GATTUSO J.-P., 1993 – *Air-Sea* CO_2 *Exchange in Coastal Ecosystems.* NATO ASI Series 14 : 233-248.
- FURLA P., ALLEMAND D., SHICK M., FERRIER-PAGÈS C., RICHIER S. *et al.*, 2005 – *The Symbiotic Anthozoan : a Physiological Chimera between Alga and Animal.* Integr Comp Biol 45 : 595-604.
- FURLA P., RICHIER S. and ALLEMAND D., 2011 – *Physiological Adaptation to Symbiosis in Cnidarians. Coral Reefs : an Ecosystem in Transition.* Springer Netherlands.
- GARCIA S. M. and DE LEIVA MORENO J. I., 2003 – *Global Overview of Marine Fisheries.* In *Responsible Fisheries in the Marine Ecosystem*. FAO & CABI Publishing.
- GATTUSO J.-P, ALLEMAND D. and FRANKIGNOULLE M., 1999 – *Photosynthesis and Calcification at Cellular, Organismal and Community Levels.* In *Coral Reefs : a Review on Interactions and Control by Carbonate Chemistry*. Am Zool 39 : 160-183.
- GATTUSO J.-P., FRANKIGNOULLE M. and WOLLAST R., 1998 – *Carbon and Carbonate Metabolism in Coastal Aquatic Ecosystems*. Annu Rev Ecol Syst 29 : 405-433.
- HOEGH-GULDBERG O., 1999 – *Climate Change, Coral Bleaching and the Future of the World's Coral Reefs.* Mar Freshwater Res 50 : 839-866.
- HOLCOMB M., VENN A. A., TAMBUTTÉ É., TAMBUTTÉ S., ALLEMAND D. *et al.*, 2014 – *Coral Calcifying Fluid Ph Dictates Response to Ocean Acidification.* Sci Rep 4 : 5207.
- HOULBRÈQUE F. and FERRIER-PAGES C., 2009 – *Heterotrophy in Tropical Scleractinian Corals*. Biol Rev. 84 : 1-17.
- MOBERG F. and FOLKE C., 1999 – *Ecological Goods and Services of Coral Reef Ecosystems.* Ecol Econ 29 : 215-233.
- MOYA A., HUISMAN L., BALL E. E., HAYWARD D. C., GRASSO L. C. *et al.*, 2012 – *Whole Transcriptome Analysis of the Coral Acropora millepora Reveals Complex Responses to* CO_2*-driven Acidification during the Initiation of Calcification*. Mol Ecol 21 : 2440-2454.

- MUSCATINE L., GOIRAN C., LAND L., JAUBERT J., CUIF J. P. *et al.*, 2005 – *Stable Isotopes (^{13}C and ^{15}N) of Organic Matrix from Coral Skeleton.* Proc Natl Acad Sci USA 102 : 1525-1530.
- PORTER J. W. and TOUGAS J. I., 2001 – *Reef Ecosystems : Threats to their Biodiversity*. In *Encyclopedia of Biodiversity*. San Diego : Academic Press.
- REYNAUD S., LECLERCQ N., ROMAINE-LIOUD S., FERRIER-PAGÈS C., JAUBERT J. *et al.*, 2003 – *Interacting Effects of CO_2 Partial Pressure and Temperature on Photosynthesis and Calcification in a Scleractinian Coral*. Global Change Biol 9 : 1660-1668.
- TAMBUTTÉ S., HOLCOMB M., FERRIER-PAGÈS C., REYNAUD S., TAMBUTTÉ É. *et al.*, 2011 – *Coral Biomineralization : from the Gene to the Environment.* J Exp Mar Biol Ecol : 58-78, 2011.
- SMITH S. V. and KINSEY D. W., 1976 – *Calcium Carbonate Production, Coral Reef Growth, and Sea Level Change.* Science 194 : 937-939.
- TAMBUTTÉ S., TAMBUTTÉ É., ZOCCOLA D. and ALLEMAND D., 2008 – *Organic Matrix and Biomineralization of Scleractinian Corals.* In *Handbook of Biomineralization*. Wiley-VCH Verlag GmbH.
- TEEB, 2010– *The Economics of Ecosystems and Biodiversity Ecological and Economic Foundations.* Pushpam Kumar, Earthscan.
- VENN A. A., TAMBUTTÉ É., HOLCOMB M., LAURENT J., ALLEMAND D. *et al.*, 2013 – *Impact of Seawater Acidification on Ph at the Tissue-Skeleton Interface and Calcification in Reef Corals.* Proc Natl Acad Sci USA 110 : 1634-1639.
- VIDAL-DUPIOL J., ZOCCOLA D., TAMBUTTÉ É., GRUNAU C., COSSEAU C.*et al.*, 2013 – *Genes Related to Ion-Transport and Energy Production Are Upregulated in Response to CO_2-Driven Ph Decrease in Corals : New Insights from Transcriptome Analysis.* PLoS One 8 : e58652.
- WEIS V. M. and ALLEMAND D., 2009 – *What Determines Coral Health ?* Science 324 : 1153-1155.
- WELLS S., 2006 – *In The Front Line Shoreline Protection and other Ecosystem Services from Mangroves and Coral Reefs.* UNEP-WCMC Biodiversity Series 24 : 1-34.
- WELLS S., 2006 – *Shoreline Protection and other Ecosystem Services from Mangroves and Coral Reefs.* UNEP-WCMC Biodiversity Series 24.

Exploited Marine Biodiversity and Climate Change

Philippe Cury

Climate change is affecting the productivity of marine ecosystems and impacting fisheries, 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 will face 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, in 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, 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 are located in the tropics and are 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). The Ecosystem Approach to Fisheries enables reconciliation of exploitation and conservation of the species; in other words it aims at maintaining the integrity and resilience of ecosystems. The EAF contributes to the crucial issue of maintaining marine ecosystems healthy and productive, while proposing a new way of considering fish exploitation in a broader context (www.fao.org/Fishery/eaf-net). The 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 has yet to be understood and assessed, thus opening many research perspectives on this subject.

REFERENCES

- POLOCZANSKA E. S., HOEGH-GULDBERG O., CHEUNG W., PÖRTNER H.-O. and BURROWS M., 2014 – *Cross-Chapter Box On Observed Global Responses Of Marine Biogeogra- Phy, Abundance, And Phenology To Climate Change.* In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A : Global and Sectoral Aspects.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- BEAUGRAND G. P., REID C., IBANEZ F., LINDLEY J. A. and EDWARDS M., 2002 – *Reorganization of North Atlantic Marine Copepod Biodiversity and Climate*. Science, 296 : 1692-1694.
- W. W. L. CHEUNG *et al.*, 2009 – *Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change*. Global Change Biology (2010) 16, 24 – 35.
- CHEUNG W. W. L., DUNNE J., SARMIENTO J. L. and PAULY D., 2011 – *Integrating Ecophysiology and Plankton Dynamics into Projected Maximum Fisheries Catch Potential under Climate Change in the Northeast Atlantic.* ICES Journal of Marine Science, 68 : 1008 – 1018.
- CHEUNG W., WATSON R. and PAULY D., 2013 – *Signature of Ocean Warming in Global Fisheries Catch.* Nature 497 : 365-368.
- GOULLETQUER P. , GROS P., BŒUF P. et WEBER J., 2013 – *Biodiversité en environnement marin*. QUAE Editions.
- HOEGH-GULDBERG O. and BRUNO J. F., 2010 – *The Impact of Climate Change on the World's Marine Ecosystems*. Science, 328, 1523-1528.
- LAM V. W. Y., CHEUNG W.W.L., SWARTZ W. and SUMAILA U. R., 2012 – *Climate Change Impacts on Fisheries in West Africa : Implications for Economic, Food and Nutritional Security*. African Journal of Marine Science, vol. 34, Issue 1, 2012: 103-117.
- PERRY I., CURY P. M., BRANDER K., JENNINGS S., MÖLLMANN C. and PLANQUE B., 2010 – *Sensitivity Of Marine Systems to Climate and Fishing : Concepts, Issues and Management Responses.* Journal of Marine Systems 79 : 427 – 435.
- PINKSY M. L., WORM B., FOGARTY M. J., SARMIENTO J. L. and LEVIN S. A., 2013 – *Marine Taxa Track Local Climate Velocities.* Science, 341,1239-1242.
- SWARTZ W., SUMAILA U.R., WATSON R.and PAULY D., 2010 – *Sourcing Seafood for the Three Major Markets : the Eu, Japan and the Usa.* Marine Policy 34 (6) : 1366-1373.

Aquaculture and Global Changes

Marc Metian

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. In fact, 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 action 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 of 90.4 million tons (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 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, 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.

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

DIVERSE VULNERABILITIES AND DIFFERENT TYPES OF PRODUCTION

Aquaculture is not performed 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.

One in particular, among the different global changes is regularly highlighted as the shellfish production on the West Coast of the United States is already experiencing its impacts: 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), produced 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 undoubtedly 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 experienced most sharply 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. Feed formulation improvements 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.

RECOMMENDED REFERENCES

- ALLISON E. H., BADJECK M.-C. and MEINHOLD K., 2011 – *The Implications of Global Climate Change for Molluscan Aquaculture, in Shellfish Aquaculture and the Environment.* Wiley-Blackwell, Oxford.
- BRANDER K. M., 2007 – *Global Fish Production and Climate Change*. PNAS 104 (50): 19709 – 19714.
- COCHRANE K., DE YOUNG C., SOTO D. and BAHRI T., 2009 – *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge.* FAO Fisheries and Aquaculture Technical Paper, n° 530. Rome.
- DE SILVA S. S. and SOTO D., 2009 – *Climate Change and Aquaculture: Potential Impacts, Adaptation and Mitigation.* In *Climate Change Implications for Fisheries and Aquaculture. Overview of Current Scientific Knowledge.* Food and Agriculture Organization of the United Nations, Rome, pp. 151–212.
- DONEY S. C., FABRY V. J., FEELY R. A. and KLEYPAS J. A., 2009 – *Ocean Acidification: the Other* CO_2 *Problem.* Annual Review of Marine Science 1: 169 – 192.
- FAO, 2014 – *The State of World Fisheries and Aquaculture.* FAO Fisheries and Aquaculture Department, Rome.
- HANDISYDE N. T., ROSS L. G., BADJECK M.-C. and ALLISON E. H., 2006 – *The Effects of Climate Change on World Aquaculture: a Global Perspective. Final Technical Report.* DFID Aquaculture and Fish Genetics Research Programme, Stirling Institute of Aquaculture, Stirling, www. aqua.stir.ac.uk/GISAP/climate/index.htm.
- MERINO G., BARANGE M., BLANCHARD J. L., HARLE J., HOLMES R., ALLEN I., ALLISON E. H., BADJECK M. C., DULVY N. K., HOLT J., JENNINGS S., MULLON C. and RODWELL L. D., 2012 – *Can Marine Fisheries and Aquaculture Meet Fish Demand from a Growing Human Population in a Changing Climate?* Global Environmental Change 22: 795 – 806.
- MERINO G., BARANGE M. and MULLON C., 2010 – *Climate Variability and Change Scenarios for a Marine Commodity: Modelling Small Pelagic Fish, Fisheries and Fishmeal in a Globalized Market.* Journal of Marine Systems 81: 196 – 205,.
- TROELL M. *et al.*, 2014 – *Does Aquaculture Add Resilience to the Global Food System?* Proceedings of the National Academy of Sciences 111 (37): 13257 – 13263.
- TACON A. G. J., METIAN M. and DE SILVA S. S., 2010 – *Climate Change, Food Security and Aquaculture: Policy Implications for Ensuring the Continued Green Growth & Sustainable Development of A Much Needed Food Sector.* In *Proceeding of the Workshop on Advancing the Aquaculture Agenda: Policies to Ensure a Sustainable Aquaculture Sector.* French Ministry for Food, Agriculture and Fisheries and OECD.
- TACON A. G. J. and METIAN M., 2008 – *Global Overview on the Use of Fish Meal and Fish Oil In Industrially Compounded Aquafeeds: Trends and Future Prospects.* Aquaculture 285 (1-4): 146-158.

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 one island system to another, Small islands in general have to face significant 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. Consequently, such societies have to face an extremely pressing challenge.

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 km^2 to several thousand km^2) 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).

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.

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 present their islands as the first victims of climate change. However, the threats to small islands are not so marginal, considering that in a certain way, they are 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 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 relay poorly 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? 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

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).

recognizing the high vulnerability of these territories to climate change. A few years later, the United Nations Conference on Environment and Development (Earth Summit, Rio, 1992) emphasized once again the particular case of small islands. 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. In fact, 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

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

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 for the Tuamotu Archipelago in French Polynesia: while the 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). In fact, 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

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.

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.

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

IMPACTS AND VULNERABILITY OF SMALL ISLANDS

To understand why small islands are at the forefront of impending environmental changes, it is necessary to go into 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 experienced, 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).

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.

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. 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 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 mankind.

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

9 Sediments produced by previous generations of coral reefs.

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.

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). First of all, 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 trees 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

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.

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.

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 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, 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 km²) and contrasts with the modesty of its land area (726km²), 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 1km² 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

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

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.

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 raises 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, engaging in immediate proactive policies 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, would be a major step forward, 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.

REFERENCES

- ARNDT D. S., BARINGER M. O. and JOHNSON M. R., 2010 – *State of the Climate 2009.* Bull Am Meteorol Soc, 91 : 1-222.
- BECKER M. B., MEYSSIGNAC C., LETETREL C., LLOVEL W., CAZENAVE A. and DELCROIX T., 2012 – *Sea Level Variations at Tropical Pacific Islands since 1950.* Global Planet. Change 80-81 : 85-98.
- CAZES-DUVAT V., PASKOFF R. et DURAND P., 2002 – *Évolution récente des deux îles coralliennes du banc des Seychelles (océan Indien occidental).* Géomorphologie, 3 : 211-222.
- CHURCH J. A. *et al.*, 2013 – *Sea Level Change.* In *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- CIAIS P. *et al.*, 2013 – *Carbon and Other Biogeochemical Cycles.* In *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- DIAMOND J., 2006 – *Effondrement : comment les sociétés décident de leur disparition ou de leur survie.* Gallimard.
- Di Piazza A., 2001 – *Terre d'abondance ou terre de misère. Représentation de la sécheresse à Nikunau (République de Kiribati, Pacifique central),* L'Homme, 157.
- DONEY S. C., FABRY V. J., FEELY R. A. and KLEYPAS J. A., 2009 – *Ocean Acidification : the Other CO_2 Problem.* Ann Rev Marine Sci 1 : 169-192.
- DUPONT J.-F., 1987 – *Les atolls et le risque cyclonique : le cas de Tuamotu.* Cahiers des sciences humaines, 23 (3-4) : 567-599.
- DUVAT V. et MAGNAN A., 2012 – *Ces îles qui pourraient disparaître.* Le Pommier-Belin.
- DUVAT V., MAGNAN A. and POUGET F., 2013 – *Exposure of Atoll Population to Coastal Erosion and Flooding : a South Tarawa Assessment, Kiribati. Sustainability Science, Special Issue on Small Islands.* 8 (3) : 423-440.
- V. DUVAT et A. MAGNAN, 2014 – *Des catastrophes… « naturelles » ?* Le Pommier-Belin.
- ETIENNE S., 2012 – *Marine Inundation Hazards in French Polynesia : Geomorphic Impacts of Tropical Cyclone Oli in February 2010.* Geological Society, London, Special Publications, 361 : 21-39.
- GATTUSO J.-P. and HANSSON L., 2011 – *Ocean Acidication.* Oxford University Press.
- GATTUSO J.-P., HOEGH-GULDBERG O. and PÖRTNER H.-O., 2014 – *Cross-Chapter Box On Coral Reefs.* In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A : Global and Sectoral Aspects.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- GATTUSO J.-P., P. BREWER G., HOEGH-GULDBERO.G, KLEYPAS J. A., PÖRTNER H.-O. and SCHMIDT D. N., 2014 – *Cross-Chapter Box on Ocean Acidification.* In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A : Global and Sectoral Aspects.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- GLYNN P. W., MATÉ J. L., BAKER A. C. and CALDERON M. O., 2001 – *Coral Bleaching and Mortality in Panama and Ecuador during the 1997-1998 El Nino Southern Oscillation Event : Spatial/Temporal Patterns and Comparisons with the 1982-1983 Event.* Bulletin of Marine Sciences, 69 : 79-109.

- HOEGH-GULDBERG O., 1999 – *Climate Change, Coral Bleaching and the Future of the Worlds' Coral Reefs.* Marine and Freshwater Resources, 50 : 839-866.
- HOEGH-GULDBERG O., 2011 – *Coral Reef Ecosystems and Anthropogenic Climate Change*. Regional Environmental Change, 1 : 215-227.
- HOEGH-GULDBERG O., CAI R., BREWER P., FABRY V., HILMI K., JUNG S., POLOCZANSKA E. and SUNDBY S., 2014 – *The Oceans.* In *Climate Change 2014: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- HOEKE R. K., MCINNES K. L., KRUGER J. C., MCNAUGHT R. J., HUNTER J. R. and SMITHERS S. G., 2013 – *Widespread Inundation of Pacific Islands Triggered by Distant-Source Wind-Waves.* Global and Planetary Change, 108 : 128-138.
- HOWES E. *et al.*, In Press – *The Physical, Chemical and Biological Impacts of Ocean Warming and Acidification.* IDDRI Study.
- HUGHES T. P. *et al.*, 2003 – *Climate Change, Human Impacts and the Resilience of Coral Reefs.* Science, 301 : 929-933.
- LEVERMANN A., CLARK P. U., MARZEION B., MILNE G. A., POLLARD D., RADIC V. and ROBINSON A., 2013 – *The Multi-Millennial Sea-Level Commitment of Global Warming,* PNAS 110 (34) : 13745 – 13750.
- MAGNAN A., DUVAT V. et POUGET F., 2013 – *L'archipel de Kiribati entre développement non durable et changement climatique : quelles recherches pour quelle adaptation ?* IDDRI Policy Briefs, 09/13.
- MAGNAN A., 2013 – *Éviter la maladaptation au changement climatique*. IDDRI Policy Briefs, 08/13.
- NURSE L., MCLEAN R., AGARD J., BRIGUGLIO L. P., DUVAT V., PELESIKOTI N., TOMPKINS E. and WEBB A., 2014 – *Small Islands.* In *Climate Change 2014: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- PÖRTNER H.-O., KARL D., BOYD P., CHEUNG W., LLUCH-COTA S. E., NOJIRI Y., SCHMIDT D. and ZAVIALOV P., 2014 – *Ocean Systems.* In *Climate Change 2014: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- RANKEY E. C., 2011 – *Nature And Stability of Atoll Island Shorelines : Gilbert Island Chain, Kiribati, Equatorial Pacific*. Sedimentology, 44 : 1859.
- RHEIN M. *et al.*, 2013 – *Observations : Ocean.* In *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- RIEGL B., 2007 – *Extreme Climatic Events and Coral Reefs : how Much Short-Term Threat from Global Change ?* Ecological studies, 192 : 315-341.
- SOLOMON S., PLATTNER G.-K., KNUTTI R. and FRIEDLINGSTEIN P., 2009 – *Irreversible Climate Change Due to Carbon Dioxide Emissions.* Proceedings of the National Academy of Sciences (USA), 106 (6) : 1704-1709.
- TURLEY C., 2005 – *The Other CO_2 Problem*. Open Democracy. www.opendemocracy.net/globalization-climate_change_debate/article_2480.jsp.
- WONG P. P., LOSADA I. J., GATTUSO J.-P., HINKEL J., KHATTABI A., MCINNES K., SAITO Y. and SALLENGER A., 2014 – *Coastal Systems and Low-Lying Areas.* In *Climate Change 2014: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.

Informing Climate Investment Priorities for Coastal Populations

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Since the 1990s, the Intergovernmental Panel on Climate Change (IPCC) has used global level analyses of vulnerability to inform investment and action against the effects of climate change. Beyond the IPCC, the practice has been used widely to understand the vulnerability of coastal areas to a variety of hazards, including climate change. These analyses, however, have been driven by objectives that change from one assessment to the next, with very different conceptualisations of vulnerability. Over time these analyses have become increasingly data intensive and complex, drawing from an ever-expanding number of indicators. Such variations in objectives, conceptualisations and data have led to different and often contradictory rankings of priority areas for climate change action. The increased complexity makes it more difficult to disentangle the root causes of these different rankings and the degree to which climate change influences vulnerability rankings, compared to other factors such as local environment factors and the adaptive capacity of populations to deal with environmental change. If these global indicator analyses were deconstructed, climate decision-makers could use them as scoping studies rather than expect them to provide comprehensive and robust priorities for investment. Such scoping studies, if they are to be truly useful to climate decision-makers, need to be simplified and harmonised to isolate climate change specific drivers. They can help target the locations for more in-depth local level analyses and should be supplemented by global level analyses of costs of climate action including technical, social and economic factors.

THE NEED FOR GLOBAL LEVEL ANALYSES TO IDENTIFY CLIMATE CHANGE IMPACTS ON COASTAL POPULATIONS AND THEIR LIVELIHOODS FOR INFORMED ACTION

More frequent extreme weather events such as 2005 hurricane Katrina in the USA and 2013 typhoon Haiyan (Yolanda) in the Philippines provide a preview of the kind of disasters that may accompany climate change and the need to identify areas at particular risk to mitigate their impact. Other long-term changes, such as sea-level rise, ocean acidification, and changes in sea surface temperature are expected to put millions of people and billions of dollars' worth of infrastructure at risk (Hoegh-Guldberg *et al.*, 2014; Ocean and Climate, 2015). Article 4.4 of the United Nations Framework Convention on Climate Change (UNFCCC) states that developed countries shall "(...) assist the developing country parties that are particularly **vulnerable** to the adverse effects of climate change in meeting costs of adaptation to those adverse effects" (emphasis added) (United Nations, 1992). In addition, international development targets such as the Millennium Development Goals (MDGs) and the Sustainable Development Goals (SDGs) have created a demand for scientific assessments at the global level that can help inform climate and development investment and action.

Global level indicator-based vulnerability analyses have become very popular as a tool to identify "developing country parties that are particularly vulnerable to the adverse effects of climate change" who will receive help from less vulnerable countries, in the form of financial transfers to "(meet the) costs of adaptation to those adverse effects" (United Nations, 1992). The Intergovernmental Panel on Climate Change (IPCC) was an early adopter of global level indicator-based vulnerability analyses in order to identify more vulnerable places in particular need of assistance to combat climate change.

In practice, though, indicator-based vulnerability analyses have faced challenges when applied at a global level. Hinkel (2011) argues that vulnerability analysis was originally designed and is best suited for application at the local level and not the global level. Indicator-based vulnerability analyses at the global level continue to be subject to much debate within the research community. There is no agreed upon approach to global indicator-based vulnerability analysis which has resulted in a variety of applications, even for those focused specifically on marine and coastal applications, and a drive for such analyses to become more data intensive and "comprehensive" over time. While all global vulnerability analyses contain useful data, the assumptions and final scores used for prioritising countries produced by such analyses are difficult to use to understand climate vulnerability and thus opportunities for climate-related investment.

The challenges that confront the global level application of vulnerability analyses for use in targeting climate-related investment include:

- a lack of harmonised conceptualisation of vulnerability and associated concepts, in particular impact and adaptive capacity,
- added to an ever expanding number of variables used for such analyses, many of which are not available reliably at the global level, resulting in increased complexity of analysis and combination of very different metrics together which make it difficult to isolate climate impacts on populations from other factors,
- a lack of consideration of the costs of action in addition to climate vulnerability and impacts.

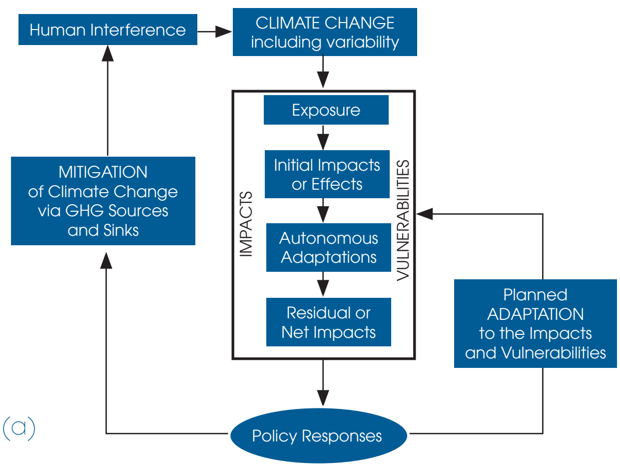
If they are to be useful to decision-makers who are focused on issues of climate change, current global level analyses should not be designed and applied as comprehensive studies but rather as scoping studies that focus clearly on the basic pathways that link climate change to impacts on people, without extending the analysis to determine overall vulnerability which is context specific. These global level "impact analyses" then could be supplemented by more refined local level analyses and analyses of costs of action to provide information useful to climate action and investment from the global down to the local level (an example at the local level is the cost effectiveness analysis by Ramirez *et al.*, forthcoming).

CONTRASTED CONCEPTUALISATIONS OF VULNERABILITY AND ASSOCIATED CONCEPTS

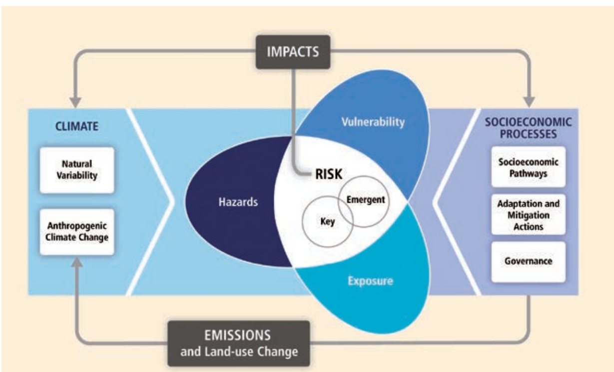
Vulnerability is a concept that is intuitively understandable and simple, allowing for integration of physical, ecological, and human impacts of climate change. The concept emerged in relation to disaster management at the local level (e.g. Weichselgartner, 2001) and has evolved over time to be used by interdisciplinary research on a number of topics including climate change (Turner *et al.*, 2003). However, the vulnerability concept lacks harmonised definition and measurement for consistent practical applications (Adger, 2006), which means it is difficult to choose among competing approaches or to understand their differences.

The lack of a harmonised definition for vulnerability can be best illustrated through the evolution of the framework used by the IPCC for vulnerability analyses at the global level between 2001 and 2014 (Figure 1a,b). In the Third Assessment Report, vulnerability was defined as "a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity" (Schneider and Sarukhan, 2001, p.90, Figure 1a). In the Fifth Assessment Report, the definition of vulnerability changes to "the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (Oppenheimer *et al.*, 2014, p.1046, Figure 1b). The concept is also applied from a variety of perspectives in the IPCC reports (vulnerability of ecosystems, populations, the economy) potentially adding to possible confusion over the message conveyed.

Even though conceptualisations differ for the definition of vulnerability, the core of the vulnerability framework remains relatively unchanged and can be boiled down to its components of hazard, exposure, sensitivity, adaptive capacity and vulnerability (Figure 2, see Schneider and Sarukhan, 2001 and Ionescu *et al.*, 2009 for more information). Key differences between the frameworks lie in the way the relationship between vulnerability and the other factors is formalised, and the feedbacks and actions that influence and are influenced by vulnerability - namely adaptation, mitigation,



(a)



(b)

Fig.1 — 2001 and 2014 conceptual frameworks used by the IPCC for vulnerability analyses. Sources: (a) Places of adaptation in the climate change issue (Schneider and Sarukhan, 2001, p.90) (b) Schematic of the interaction among the physical climate system, exposure, and vulnerability producing risk (Oppenheimer et al., 2014, p.1046).

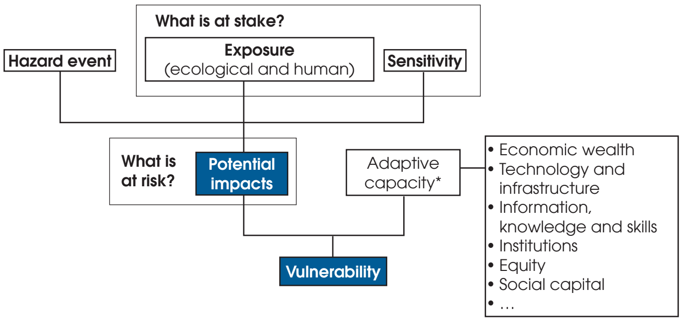


Fig.2 — Contributing factors to potential impacts and vulnerability (adapted from Schneider and Sarukhan, 2001 and Ionescu et al., 2009). Non bold: (Descriptive) factors contributing to vulnerability; bold: predictive and speculative outcomes; * Adaptive capacity tends to be the most context specific.

and governance. This flexibility in the framework makes the vulnerability concept well suited to analysis at the local level, where more context-specific information is available (Hinkel, 2011). It makes however the concept more difficult to use at the global level in a consistent way, which would require more of a 'blueprint' approach to be a comparative guide to investment across different types of risks and social contexts.

A number of global indicator analyses, applied to marine resources, have been conducted by academics (e.g. Allison *et al.*, 2009; Barange *et al.*, 2014; Cooley *et al.*, 2012, Hughes *et al.*, 2012; Halpern *et al.*, 2012) and NGOs (Burke *et al.*, 2011; Beck, 2014; Harrould-Kolieb *et al.*, 2009, Huelsenbeck 2012) to assess ocean health and the specific risks faced by coral reefs and the people that depend upon them. Each has appropriated and redefined the core concepts of the approach differently. Even when definitions are common, the indicators and corresponding datasets used to measure hazard, exposure, sensitivity, adaptive capacity as well as the formulae used to calculate vulnerability itself vary across these studies, mostly in relation to available data and specific focus of these studies.

Lack of agreed definition and measure of vulnerability, ambiguous use of the concept for multiple perspectives (what/who is vulnerable to what changes), have partly impaired the establishment of global analyses that help set up clear priorities for climate investment and action.

WHAT DO GLOBAL VULNERABILITY ANALYSES ACTUALLY REVEAL: UNDERSTANDING CONFLICTING VULNERABILITY RANKINGS FROM CLIMATE CHANGE IMPACTS ON COASTAL HUMAN POPULATIONS

Conceptual differences and different indicators used in global analyses of coastal and marine risks have led to very different rankings of priorities for countries at risk. Table 1 shows a large number of different countries that appear in the top 10 in terms of vulnerability or poor ocean health. Of these, 35 appear in the top 10 of only one of the reports.

In an effort to be more comprehensive and to reflect the different abilities of coastal populations to deal with climate change, recent indicator-based global level analyses include coping and adaptive capacities. All but one of these studies includes measures of capacity (Harrould-Kolieb *et al.*, 2009). There are two immediate consequences of the use of capacity measures in these analyses. First, developed countries that face large potential impacts from climate change never rank high – even though the value of needed climate-change related investment may be extremely large. Second, it becomes difficult to know, using final scores alone, whether a high indicator score is due to vulnerability caused by climate change or inherent vulnerabilities caused by demographic, political, and social factors. Some empirical work suggests that global adaptive capacity indicators can be identified (Brooks *et al.*, 2005) but they so far reflect generic issues such as education and poverty that may be very important for development and well-being but not necessarily for dealing with sectoral impacts of climate change (Hughes *et al.*, 2012).

A TWO-TIERED APPROACH FOR GLOBAL ANALYSIS TO INFORM CLIMATE INVESTMENT AND ACTION

To avoid the challenges described above and to move towards a more transparent approach to global indicator analyses that can be used to identify climate action, we need a simplification and harmonisation of analyses to understand the impacts of climate change, and global environmental change, at the global level for coastal human populations.

Specifically, we suggest a two-tiered approach for classifying existing studies to better identify common elements, and guide further global analysis (Figure 3):

1. GLOBAL LEVEL IMPACT ANALYSES (first tier): At the global level, we should focus on **simplified and more standardised** scoping analyses for which good global data are available. These simpler approaches should link climate change directly to impact, be limited to impacts, and not include measures of adaptive capacity so as to clearly separate development issues from threats driven by climate change. A focus on global-level impact analyses can help identify countries where:

a. climate action may be warranted (mitigation, adaptation or other),
b. additional, finer scaled vulnerability analysis may provide crucial information to set up appropriate policy action, and
c. monitoring and science may yield socially relevant results.

The scores used to rank countries could be presented by impact or as a summary measure of how high-ranked countries scored across the impacts considered. Global-level scoping analyses based on impacts are meant to guide more refined and more data-intensive local level analyses, but do not aim to replace such local level analyses. Ideally, such analyses are accompanied by a global scale analysis of technical, economic and social costs of action for comparison to potential benefits from impact mitigation and adaptation.

2. LOCAL LEVEL ANALYSES (second tier): The global scoping analyses will identify places where more thorough, and more **comprehensive local level analyses** can be used to identify concrete investment actions and the degree to which these places are vulnerable to climate change. At the local level, more refined, data-intensive analysis can be used to better understand local impacts of global and local changes and be-

RanK	Reef at risk revisited (Burke *et al.*, 2011)	Coasts at risk (Beck, 2014)	Allison *et al.*, 2009	Ocean Health Index (Halpern *et al.*, 2014)	Oceana (Harrould-Kolieb *et al.*, 2009)	Oceana (Huelsenbeck, 2012)
1	Comoros	**Antigua-and-Barbuda**	**Angola**	**Saint- Vincent-and- Grenadines**	**Japan**	Comoros
2	Fiji	Tonga	RD Congo	Haïti	**France**	**Togo**
3	**Grenada**	**Saint-Kitts-and-Nevis**	**Russian Federation**	**Ivory Coast**	**United Kingdom**	**Cook Islands**
4	Haïti	Vanuatu	**Mauritania**	Sierra Leone	**Netherlands**	Kiribati
5	Indonesia	Fiji	**Senegal**	**Nicaragua**	**Australia**	**Erythrea**
6	Kiribati	**Brunei Darussalam**	**Mali**	**Libya**	**New Zealand**	Mozambique
7	Philippines	**Bangladesh**	Sierra Leone	RD Congo	Philippines	**Madagascar**
8	**Tanzania**	Philippines	Mozambique	**East Timor**	**United States**	**Pakistan**
9	Vanuatu	**Seychelles**	**Niger**	**Dominica**	**Malaysia**	Sierra Leone
10		Kiribati	**Peru**	**Liberia**	Indonesia	**Thailand**

Table 1 — Examples of rankings for coastal communities at risk from climate change. In bold, countries found in the top 10 of only one of the reports.

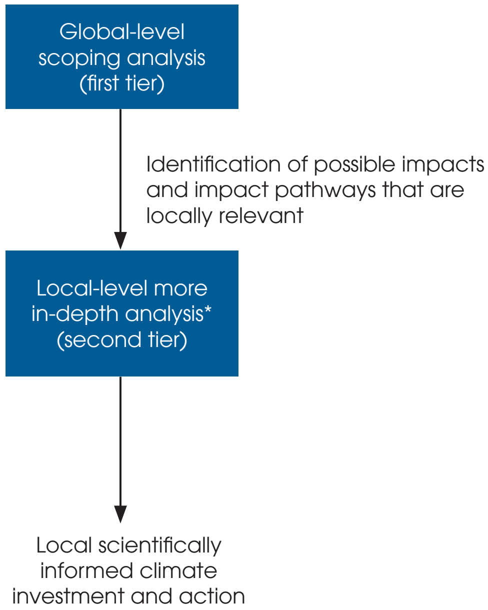


Fig.3 — Stratégie à deux niveaux pour l'analyse scientifique et l'action informée (*comprend l'étude et le suivi de la vulnérabilité).

haviours. Such analyses would include, but not be limited to, vulnerability analyses, and would help identify key environmental and ecological factors affecting human dependencies which are most impacted by climate change. There already exists a number of relevant local level analyses which have been successfully applied in developed and developing countries that could be better used to understand climate impacts and actions (e.g. Cinner *et al.*, 2012; Ekstrom *et al.*, 2015; Yusuf and Francisco, 2010; Arias *et al.*, forthcoming; Sajise *et al.*, forthcoming).

This two-tiered approach is a pragmatic way to make the most of available data, approaches and scientific methods to undertake meaningful analyses that can guide climate action and help prioritise efforts where most urgently needed. It also helps provide a global-level, transparent framework while keeping local flexibility for climate investment and action from the global down to the local level. Like vulnerability analysis, the approach combines natural and social sciences to understand the potential impacts on people of climate change, but it does so at levels that better match the social science concepts to the scale at which relevant data are available. The first tier allows for meaningful policy recommendations at the global level, while the second tier provides the needed flexibility in relation to changing spatial and human contexts.

Such a two-tiered approach still requires continued improvements in the quality and quantity of natural and social science data. While natural science data regarding climate, oceanography, corals and fisheries continues to improve, human data lag behind, especially data about local fisheries, tourism and the built environment.

CONCLUSION

The first tier of the two-tiered approach could be useful to identify all countries that are likely to experience large direct or indirect impacts from climate change. If applied to a pool of recipient countries alone (*i.e.* developing countries under Article 4.4 of the UNFCCC receiving international transfers), such a tier could be used to identify places where foreign assistance to meeting the costs of adaptation under the UNFCCC may be most useful. The second tier could be used by developed and developing countries alike to inform more fine-tuned context-appropriate investment within countries, and not just international transfers. This second tier can consider different types of action, including climate change action but not exclusively, and different investment options into mitigation, adaptation and science.

In addition to the two tiers proposed here, we also urge a parallel but separate global scale analysis of costs of action including technical, social and economic factors is conducted. The combination of the two-tiered approach and global scale analysis of costs of action should provide necessary information for informed climate investment and action.

REFERENCES

- ADGER W.N., 2006 – *Vulnerability. Global Environmental Change.* 16 (3) : 268-281.
- ALLISON E.H., PERRY A.L., BADJECK M.-C., ADGER W. N., BROWN K., CONWAY D., HALLS A.S., PILLING G.M., REYNOLDS J.D., ANDREW N.L. and DULVY N.K., 2009 – *Vulnerability of National Economies to the Impacts of Climate Change on Fisheries.* Fish and Fisheries, 10 (2) : 173-196.
- ARIAS J.K.B, PEREZ M.L., SAJISE A.J.U, RAMIREZ P.J.B., PURNOMO A.H., DIPASUPIL S.R., REGONIEL P.A., NGUYEN K.A.T. and ZAMORA G.J. – *Household Vulnerability and Impacts of Climate Hazards in Coastal Communities in Southeast Asia.* EEPSEA publication, en cours de publication.
- BARANGE M., MERINO G., BLANCHARD J.L., SCHOLTENS J., HARLE J., ALLISON E.H., ALLEN J.I., HOLT J. and JENNINGS S., 2014 – *Impacts of Climate Change on Marine Ecosystem Production in Societies Dependent on Fisheries.* Nature Climate Change, 4 : 211-216.
- BECK M. W. (ed.), 2014 – *Coasts at Risk : An Assessment of Coastal Risks and the Role of Environmental Solutions.* A joint publication of United Nations University - Institute for Environment and Human Security (UNU-EHS), The Nature Conservancy (TNC) and the Coastal Resources Center (CRC) at the University of Rhode Island Graduate School of Oceanography, http://www.crc.uri.edu/download/SUC09_CoastsatRisk.pdf, 85 pages.
- BROOKS N., ADGER W.N. and KELLY P.M., 2005 – *The Determinants of Vulnerability and Adaptive Capacity at the National Level and the Implications for Adaptation.* Global Environmental Change, 15 (2) : 151 – 163.
- BURKE L., REYTAR K., SPALDING M. and PERRY A., 2011 – *Reefs at Risk Revisited.* World Resources Institute (WRI), 130 pages.
- CINNER J. E., McCLANAHAN T. R., GRAHAM N. A. J., DAW T. M., MAINA J., STEAD S. M., WAMUKOTA A., BROWN K. and BODIN Ö., 2012 – *Vulnerability of Coastal Communities to Key Impacts of Climate Change on Coral Reef Fisheries.* Global Environmental Change, 22 (1), 12 – 20.
- COOLEY S.R, LUCEY N., KITE-POWELL H. and DONEY S.C., 2012 – *Nutrition and Income from Molluscs Today Imply Vulnerability to Ocean Acidification Tomorrow.* Fish and Fisheries, 13 (2), 182 – 215.
- EKSTROM J. A., SUATONI L., COOLEY S. R., PENDLETON L. H., WALDBUSSER G. G., CINNER J. E., RITTER J., LANGDON C., VAN HOOIDONK R., GLEDHILL D., WELLMAN K., BECK M.W., BRANDER L.M., RITTSCHOF D., DOHERTY C., EDWARDS P.E.T. and PORTELA R., 2015 – *Vulnerability and Adaptation of us Shellfisheries to Ocean Acidification.* Nature Publishing Group, 5 (3), 207 – 214.
- HALPERN B.S., LONGO C., HARDY D., MCLEOD K.L., SAMHOURI J.F., KATONA S.K., KLEISNER K., LESTER S.E., O'LEARY J., RANELLETTI M., ROSENBERG A.A., SCARBOROUGH C., SELIG E.R., BEST B.D., BRUMBAUGH D.R., CHAPIN F.S., CROWDER L.B., DALY K.L., DONEY S.C., ELFES C., FOGARTY M.J., GAINES S.D., JACOBSEN K.I., KARRER L.B., LESLIE H.M., NEELEY E., PAULY D., POLASKY S., RIS B., ST MARTIN K., STONE G.S., SUMAILA U.R. and ZELLER D., 2012 – *An Index to Assess the Health and Benefits of the Global Ocean.* Nature, 488 : 615-620.
- HARROULD-KOLIEB E., HIRSHFIELD M. and BROSIUS A., 2009 – *Major Emitters Among Hardest Hit by Ocean Acidification.* Oceana.
- HINKEL J., 2011 – *"Indicators of vulnerability and adaptive capacity" : Towards a clarification of the science – policy interface.* Global Environmental Change, 21 (1) : 198 – 208.
- HOEGH-GULDBERG O., CAI R., POLOCZANSKA E.S., BREWER P.G., SUNDBY S., HILMI K., FABRY V.J. and JUNG S., 2014 – *The Ocean. In : Climate Change 2014: Impacts, Adaptation, and Vulnerability.* Part A : Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (FIELD C.B., BARROS V.R., DOKKEN D.J., MACH K.J., MASTRANDREA M.D., BILIR T.E., CHATTERJEE M., EBI K.L., ESTRADA Y.O., GENOVA R.C., GIRMA B., KISSEL E.S., LEVY A.N., MACCRACKEN S., MASTRANDREA P.R. and WHITE L.L. (eds.)). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1655-1731.
- HUELSENBECK M., 2012 – *Ocean-Based Food Security Threatened in a High CO_2 World.* Oceana, http://oceanacidification.co.uk/pdf/1acid_final_091812-pdf.pdf, 16 pages.
- HUGHES S., YAU A., MAX L., PETROVIC N., DAVENPORT F., MARSHALL M., MCCLANAHAN T.R., ALLISON E.H. and CINNER J.E., 2012 – *A Framework to Assess National Level Vulnerability from The Perspective of Food Security : the Case of Coral Reef Fisheries.* Environmental Science & Policy, 23 : 95 – 108.

- IONESCU C., KLEIN R.J.T., HINKEL J., KAVI KUMAR K.S. and KLEIN R., 2009 – *Towards a Formal Framework of Vulnerability to Climate Change.* Environmental Modeling & Assessment, 14: 1-16.
- NATIONS UNIES, 1992 – *The United Nations Framework Convention on Climate Change (UNFCCC).*
- OCÉAN ET CLIMAT, 2015 – *Fiches scientifiques.* www.ocean-climate.org.
- OPPENHEIMER M., CAMPOS M., WARREN R., BIRKMANN J., LUBER G., O'NEILL B. and TAKAHASHI K., 2014 – *Emergent risks and key vulnerabilities.* In : *Climate Change 2014: Impacts, Adaptation, and Vulnerability.* Part A : Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (FIELD C.B., BARROS V.R., DOKKEN D.J., MACH K.J., MASTRANDREA M.D., BILIR T.E., CHATTERJEE M., EBI K.L., ESTRADA Y.O., GENOVA R.C., GIRMA B., KISSEL E.S., LEVY A.N., MACCRACKEN S., MASTRANDREA P.R., and WHITE L.L. (eds.)). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039-1099.
- RAMIREZ P.J.B., PEREZ M.L., ARIAS J.K.B, SAJISE A.J.U, PURNOMO A.H., DIPASUPIL S.R., REGONIEL P.A., NGUYEN K.A.T. and ZAMORA G.J., in press – *Cost Effectiveness Analysis of Public Adaptation Options in Coastal Communities in Southeast Asia.* EEPSEA publication.
- SAJISE A.J.U., PEREZ M.L., ARIAS J.K.B, RAMIREZ P.J.B., PURNOMO A.H., DIPASUPIL S.R., REGONIEL P.A., NGUYEN K.A.T. and ZAMORA G.J. – *Determinants of Autonomous Adaptive Behavior in Coastal Communities in Southeast Asia.* EEPSEA publication, en cours de publication.
- SCHNEIDER S. and SARUKHAN J., 2001 – *Overview of Impacts, Adaptation, and Vulnerability to Climate Change.* In *Climate Change 2001: Working Group II : Impacts, Adaptation and Vulnerability.* www.grida.no/publications/other/ipcc_tar/, 30 pages.
- TURNER B. L. II, KASPERSON R.E., MATSON P.A., MCCARTHY J.J., CORELL R.W., CHRISTENSEN L., ECKLEY N., KASPERSON J.X., LUERS A., Martello M.L., POLSKY C., PULSIPHER A. and SCHILLER A., 2003 – *A framework for vulnerability analysis in sustainability science.* Proceedings of the National Academy of Sciences, 100 (14) : 8074 – 8079.
- WEICHSELGARTNER J., 2001 – *Disaster Mitigation : the Concept of Vulnerability Revisited.* Disaster Prevention and Management : An International Journal, 10 (2) : 85-95.
- YUSUF A.A. and FRANCISCO H., 2010 – *Hotspots ! Mapping Climate Change Vulnerability in Southeast Asia.* Economy and Environment Program for Southeast Asia. http://www.eepsea.org/pub/book/Coffee_Book_Final_29Sep10.pdf.

Lifestyles and attitudes in Tabiteuea: a dam against the Pacific?

Guigone Camus

Kiribati archipelago mythology teaches us that the world began with a crack in a rock, followed by a mixture between dry and moist matter and finally by the prolific efflorescence of a crowd of creative ancestors. Scientific facts in the western world warn that within less than 300 years, these Eastern Micronesian atolls will disappear as a result of rising sea level due to global warming. Ethnographic fieldwork demonstrates how these people of Oceania, who settled in the heart of the Pacific more than a thousand years ago, have the dignity to interpret present climate instability with remarkable philosophical intelligence. Climate change reveals the reality of this duel between the survival of so-called modern progress that continues to endanger the future of the planet on one hand, and the survival of traditional ways of living with the belief that Man evolves in a respected natural environment on the other hand. These two confronting issues will be presented at the coming Climate Conference in Paris. Is it such a utopian concept to expect the decision-makers to offer a sacrifice to Mother Nature?

FROM THE MYTH OF CREATION TO THE REALITY OF DESTRUCTION

Imagine thirty-three coral confetti, scattered on each side of the equator across a broad Pacific area as large as the European Union. This might suggest a first idea of what the Kiribati archipelago looks like. Perhaps you would rather imagine that in the Beginning the world was a closed semi spherical Rock on top of which walked an ancestral Spider, named Naareau, who was endowed with considerable magical powers. After spending some time meditating while wandering to and fro between the four cardinal points, Naareau began to crack the world's surface in order to extract two vital principles: Sand and Moisture. From the mixture of these two materials in the palm of his left hand, Naareau the Second emerged, filled with Knowledge and Science. He roused assemblies of spirits from the realms of heaven, sea, land and time, who were to assist him with the development of the World. The Moray Eel ancestor stood up to lift and stabilize the heavens, the Great-Father ancestor sacrificed his eyes to give birth to the Sun and the Moon, his arms and legs so they may bring the Seasons, his flesh so it might scatter across the Sky to form the Stars, and his intestines to fill the Land and Sea with all living species. Finally Naareau the Second created the atolls that he populated with a group of ancestors who had been, until then, perched on a mythical tree. This is how the ancestors of the present occupants of Kiribati are to have appeared.

The islander's metaphysics, conveyed by storytellers, but also, by missionaries since the introduction of writing, in the form of precious notebooks recounting their mythologies and genealogies, require a predisposition for reverie. Whoever shows an interest towards their vision of this small fragmented world, lost within the vast oceanic domain is inevitably drawn into a state of contemplation from which it is difficult to escape. There exists, however, a harsh reality that does tear one away from this state of daydreaming: "Climate Change". Bearing a warning of what the planet might experience in a few decades, the 811 km² of emerged coral atolls of the Kiribati archipelago already display scars due to the irresponsibility of post-industrial Mankind. Erosion, storms, droughts, the drying up of fresh groundwater lenses, the depletion of flora and fauna in lagoon and ocean waters, increasingly vulnerable land resources ... All these signs have spoiled the poetic interpretation of the surrounding world portrayed by the local mythology of these islands.

THE ISLAND REPUBLIC OF KIRIBATI: A FEW BENCHMARKS

Created with the association of three Oceanian archipelagos[1], the independent Republic of Kiribati presently boasts a population of over 100,000 people, the majority having settled in the former Gilbert Islands for more than a thousand years. Since its independence in 1979, it is run by a President and represented by a Parliament. At an island scale, the Island Council has a strong discretionary power and at a village level (particularly in the Southern Gilbert Islands), community affairs still animate collective debates in the traditional meeting house, called the *maneaba*.

Kiribati mainly gets its low GDP from the sale of frozen fish, copra and fishing licenses. It was classed as a SIDS and LDC[2], and relies on international aid for development issues; the same reliance holds for strategies against the effects of climate change.

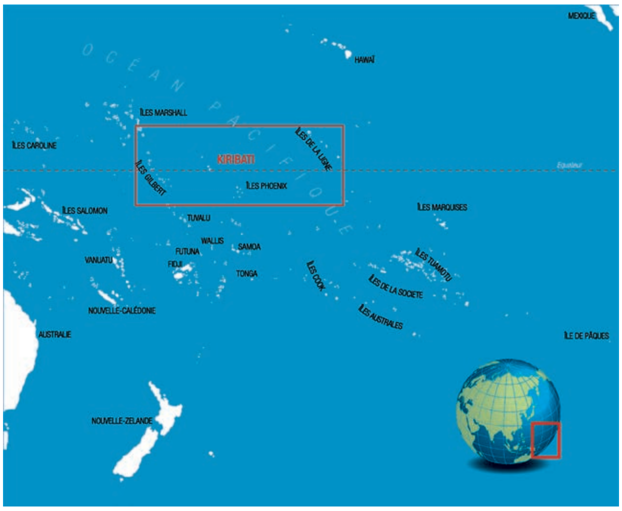


Fig.1 — The Republic of Kiribati, within the Pacific. © Fondation culturelle Musée Barbier-Mueller, Carte Helder Da Silva.

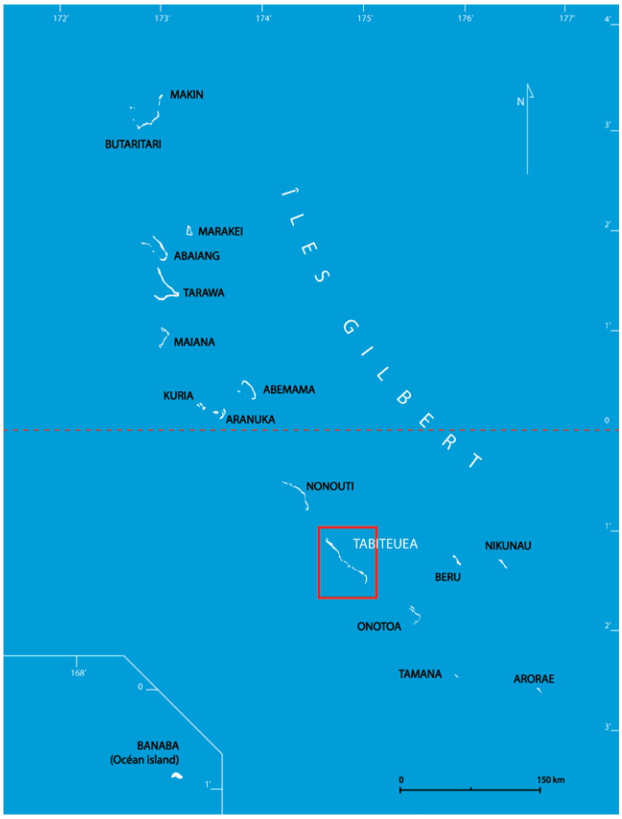


Fig.2 — Tabiteuea belongs to the Gilbert Islands, which is part of the Republic of Kiribati (with the Phoenix and the Line Islands). © Fondation culturelle Musée Barbier-Mueller, Carte Helder Da Silva.

1 The archipelago of Kiribati consists of 31 flat coral atolls and two raised atolls (Banaba and Kiritimati) covering a maritime zone of 5 million km², of which 3.5 million km² of EEZ.

2 SIDS: Small Island Developing States, LDCs: Least Developed Countries.

THE FRAGILITY OF AN ISLAND

Amongst the thirty-three atolls of the archipelago, twenty-one are occupied and all - except for the raised Banaba and Kiritimati atolls - are hardly emerged from the surface of the water.

Tabiteuea, the largest island, stretches out over 70 km long like a coral snake beneath the equator. Apart from a road, a short runway and a barely operational hospital, infrastructure on the atoll is virtually inexistent. Its 5,000 inhabitants cover an area of about 40 km^2, crossed from north to south by a sandy road that sometimes extends into the lagoon to connect certain motus[3].

As in all the Southern Islands, temperatures are hottest from April to November[4]. This climate constrains and shapes the diversity of trees and crop plants. In addition there is the geological drawback of a sterile soil as it is essentially composed of limestone and almost bereft of humus. Coconut, pandanus, breadfruit and swamp taro are the major food sources for the local population of Tabiteuea who exploits these resources and manages the food stocks with care, caution and anticipation. This controlled management of the environment by the islanders demonstrates their willingness to preserve, at all costs and in consideration of the modernity they are acquainted with[5], a conservative traditional lifestyle, which they refer to in English as "a simple life, with a simple food". This way of life involves a strong reliance on endemic plants and marine resources. It gives them a sense of pride and self-satisfaction, especially towards the *I-Matang*, or " White People", but also towards the highly urbanized capital atoll, Tarawa, where imported products have replaced local products. Nonetheless, today they have to admit that, in recent years, unstable weather events have gained intensity and are becoming more frequent, thus threatening their way of life based on self-sufficiency.

The long-term droughts and the observed increase in air temperature weaken the canopy: coconuts are smaller, swamp taro pits are drying up and their compost is rotting. This heat also dissuades the people from working and fishing as long as before during the day.

Erratic rainfall is altering the renewal of fresh water in the Ghyben-Herzberg underground lens. Not only is salt seeping in but the drinking water is becoming unhealthy and causing diseases (the number of cases of dysentery is currently rising throughout the archipelago). On some motu, the depletion of this lens is forcing people to move to other islets so as to have access to drinking water.

Although rainwater remains an acceptable source of water, storage processes also present sanitary issues. The large filter tanks are reserved for churches, schools and clinics. As for family groups, their only solution is to collect rainwater running through makeshift gutters from corrugated iron roofs into homemade tanks. These reconditioned oil drums, cracker boxes or plastic containers most often sit open in the sun, undergoing contamination by insects, dust and other wind-blown debris.

The coastlines are being eroded by increasingly invasive waves related to the rising frequency of extreme spring tides (a doubling has been observed this year) as well as to increasingly violent storm events. Along the lagoon, many homes face the threat of having to migrate inland. This should be perfectly feasible given the removable nature of the plant architecture; however a forced reduction in the size of individual or family land holdings remains an issue.

To date, mangrove swamps and seawalls remain the only solution to fight against erosion and partial flooding caused by waves and swells. Mangrove planting attempts have failed because of disputes relating to the choice of villages that would benefit from them, but also because of the questioning of the legitimacy

3 The stretches of road across the lagoon are built of concrete and covered with sand.

4 Life in the Kiribati archipelago swings between the dry and wet seasons.

5 As in all the outer islands of Kiribati, products of foreign origin (Australia, Fiji, Asia) are imported by cargo ship; they are essentially composed of rice, flour, fuel, clothing, and plastic objects for household use.

of people having volunteered for the job. The Tabiteuean society promotes an egalitarian rule that severely limits the differentiation of individuals demonstrating personal initiatives. As for the construction of seawalls, although they provide a sense of protection over a short term, they are not without consequence on the natural circulation of currents and on sedimentation in the lagoon.

Finally, the observed increase in lagoon water temperature has been associated with the reduction in the size of giant clams, with the depletion or disappearance of certain species of fish and turtles, as well as the suffocation of entire schools of fish. As for the large pelagic organisms in the ocean, they tend to retreat further away from the coast. This forces fishermen to venture farther offshore, thus increasing the risk of disappearance at sea.

THE PHILOSOPHY OF KIRIBATI: A RESPONSE TO THE DEGRADATION OF WORLD ORDER

Although the intensification of climate disturbance as well as its impact on their environment has been acknowledged, the people of Tabiteuea continue untroubled and as they have always done, to exploit their natural resources along with a form of ecological awareness that involves caution and respect for nature. These precautionary principles, being the best weapons against environmental changes, are by no means applied due to the present-day necessity of adaptation to climate change. Instead, they are rather employed to maintain the honour granted by the preservation of this "simple life", based on a minimal dependence upon import products and environmentally damaging infrastructures.

Even if the islanders have inevitably heard about climate change on the radio and how it worries the "White people", they don't feel the urge to establish causal links between the scientific determinants of climate change (as defined by Western science) and their consequences. Although they do suffer on a daily basis from these consequences, plans to avoid danger, the reduction of risk to zero or the deployment of protection strategies against the risk of flooding, are concerns that lie far from the islander's notions of life.

Some call it fatalism, unconsciousness, indifference or even inertia. It is nothing of the sort, but rather what one can describe as a " philosophy of the event": A climate event, absorbed by a society, that is capable of reaching out irreversibly towards its own essence and that prefers to keep a distance from the discontent of Western civilization. The frantic wearing-out of our planet, which is so dominant a subject in modern-day preoccupations, is not considered as an event for local discourse. This reflects, in our view, a capacity of absorption towards the unexpected and a true intellectual plasticity and physical force against the disruption of world order; a force that deserves a stronger admiration and respect from our side of the planet.

Fig.3 — Woman from the village of Kabuna, keeper of the mythical cave of Tebweka.

BEYOND ALTERITY

Today, the tricky question is how long this virtuous circle of conservatism, so particular to Tabiteuea, will be able to withstand the changes in the world. It is heart-breaking to imagine that, according to forecasts of specialists, its inhabitants will soon have to give up a part of themselves to contribute to closing our holes in the ozone layer. It is unacceptable to listen to the industrial powers invite the people of Kiribati - and all the other small populations of the Ocean, to 'adapt' and to be 'resilient', while, predicting the weather, they keep striving to destroy hundreds of millions of years of geological strata. Once more, it is amazing to realize that the impassivity of life in Tabiteuea certainly illustrates how much the islanders understand human nature, enough to feel that there is not much to hope for.

This article results from two oral statements: a presentation of the results of a survey conducted in Kiribati for the French Development Agency (AFD) June 25th 2015 (Papeete, Tahiti), and a lecture given during the symposium: Polynesia Against Climate Threats (PACT) June 30th 2015 (Papeete, Tahiti).

REFERENCES

- *Climate Variability, Extremes and Change in the Western Tropical Pacific: New Science and Updated Country Reports 2014*. Australian Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organisation (CSIRO), 2014.
- *Kiribati Joint Implement Plan for Climate Change and Disaster Risk Management KJIP, 2014-2023*. Government of Kiribati, 2014.
- *Tabiteuea North 2008 socio-economic profile*. Produced by the Ministry of Internal and Social Affairs, with Financial support from the UN Development Program & KAP and Technical Assistance from the SPC.
- CAMUS G. – *Tabiteuea Kiribati*. Hazan, 2014.
- LUOMALA K. – *Ethnobotany of the Gilbert Islands*. Bernice P. Bishop Museum Bulletin, 213, Honolulu, Hawai'i, 1953.
- LATOUCHE J.-P. – *Mythistoire Tungaru : cosmologies et généalogies aux îles Gilbert*. Paris, SELAF, 1984.
- MAUDE H. (Ed.) – *Tungaru Traditions. Writings on the Atoll Culture of the Gilbert Islands (by Arthur Francis Grimble)*. Honolulu, University of Hawai'i Press, 1989.

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Scientific committee

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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