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OCEAN AND CLIMATE
SCIENTIFIC NOTES

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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 negotiations.

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 forests.

The ocean is therefore the principal "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 – has been degrading 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

During COP21, the Ocean and Climate Platform emphasized the importance of "a healthy ocean, a protected climate". It is important to continue to show how the ocean is affected by climate change, and more importantly to show that "the ocean is part of the solution" against climate change.

After the signature of the Paris Agreement, the Platform has decided to pursue its action, in the field of scientific knowledge, ecosystem based management, maritime transport and mobilization based on solid scientific grounds and its advocacy for the integration of the ocean in the climate regime. The Platform has chosen to focus on 4 lines and to develop different topics in relation to economic solutions and nature based solutions in order to incorporate them into the Paris Agreement.

- The first central line of the Platform refers to the international reinforcement of the Scientific Committee and network for the production and dissemination of climate solution. The Platform supports international scientific collaboration, notably in the framework of FACT-O (French American Climate Talks on Ocean) which aims at promoting innovative solutions at a global scale. These solutions will feed the advocacy thematic, define the ocean and climate science needs and feed the argument for an ocean report with the IPCC.

- The second line identified within the economic solutions is the development of maritime transportation involved in the reduction of greenhouse gas emissions.

- The third line focuses on ecosystems resilience issues regarding climate change, including the key role of marine protected areas (MPAs).

- The fourth line is that of citizens and youth mobilization regarding June 8th World Ocean Day and mobilization days for Ocean and Climate issues (Ocean for Climate Days) during the Conferences of the Parties of the United Nations Framework Convention on Climate Change. This mobilization focuses on advocacy toward public and private decision makers, disseminates scientific knowledge and raises awareness toward the general public. June 8th and the Ocean for Climate Days will become an international must for ocean and climate issues relayed on the web at the international level. Many other converging events will punctuate the year 2016.

As a transversal approach to these four lines, the Platform follows the climate negotiation in order to facilitate the integration of ocean and climate advocacy. Lastly, the Platform develops alliances with States committed to the integration of the ocean in climate issues and of the climate in ocean governance.

This year and beyond, depending on opportunities, the Platform will be able to generate new topics within the "economic solutions" line, including Marine Renewable Energies (MRE) and within "ecosystem based management" including the consideration of blue carbon in the climate regime. Lastly, in the end the Platform can develop a regional complementary approach to expand these lines.

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Foreword

Françoise Gaill

The ocean is an essential component of our planet's climate. Scientists know this, and have repeatedly proven it: without the ocean, our greenhouse gas emissions would have disrupted the climate machine to a much greater extent. It is hence an essential regulator that is constantly threatened by human activity and by the consequences of global climate change.

The numbers speak for themselves. The ocean covers 71% of the planet, represents 97% of its living space, holds 97% of the Earth's water, absorbs 90% of the heat and 25% of the additional CO_2 emitted by humans. It provides livelihoods for a substantial part of the world population and provides a substantial amount of pharmaceutical substances. Its ecosystems are worth more than the United States of America's GDP. The threats facing the ocean and the communities that depend on it are as staggering as they are alarming: acidification, warming waters, deoxygenation, rising sea-levels…

Yet, despite the threats the ocean faces, despite its prevalence in the climate's inertia, it has been swept aside from international efforts to mitigate and adapt to climate change. For over twenty years, the ocean had not been mentioned in the additional texts of the United Nations Framework Convention on Climate Change (UNFCCC). Startled by this realisation, the 70 members of the Ocean and Climate Platform (public institutions, NGOs, universities, etc.) decided to give a voice to the ocean during the climate negotiations at COP21.

According to them, the Paris Agreement symbolises an important step, an outstanding success, for the inclusion of "ocean and climate" issues. For the first time since the UNFCCC, the Paris Agreement of December 2015 explicitly mentions the ocean in its preamble. Moreover, the Intergovernmental Panel on Climate Change (IPCC) will publish a Special Report on Climate change and the oceans and the cryosphere. The ocean has now entered the climate negotiations!

But the fight for the ocean does not stop here. It is no longer solely up to diplomacy – which must still better integrate the ocean – to mobilise. The marine civil society must take part in the Action Agenda, suggest alternatives, bring forth and support initiatives, communicate good practices and disseminate knowledge. The Ocean and Climate Platform is already on this path.

But above all, we must better understand the ocean – this vast, wide, diverse environment that contains so much biodiversity that has yet to be explored. The sea-bed embodies the last terra incognita. Physical and biological mechanisms are yet unexplained or poorly known. Scientists and policy-makers need to take action to fill the knowledge gaps on the relationships between the ocean and the climate. Last year, thanks to its strong scientific basis, the Ocean and Climate Platform published 17 scientific notes. In 2016 it extends this base by publishing the second volume.

This booklet seeks to be more inclusive and open. These notes embrace both "hard" and "human" sciences as we are convinced that "human" sciences are the second backbone to better know the ocean and the related socio-economic issues. The Ocean and Climate Platform welcomes new themes: the law for the ocean and climate, political sciences, human migrations… These new topics are meant to be food for thought in the international discussion on adaptation strategies, knowledge gaps, everyday behaviour, and form the basis for a better understanding of human challenges and solutions. We urge for a greater integration of "hard" sciences and "human" sciences alike. As to find solutions to global problems (climate change), research must be trans-disciplinary and holistic.

"Ocean and climate" science is a work in progress. It must respond to tremendous challenges: collecting sufficient and diverse data, reducing scales, understanding the local and global phenomena, studying the surface and the depths, the open-sea and the coast, biodiversity and human communities. The potential for research is massive. But it is absolutely necessary. The ocean is our "all-risk" insurance policy, and it is high time to protect it!

This set of articles goes back over some that were written for the COP21, updating data with recent advances in knowledge. This is the case for those on sea-level rise, ocean oxygenation, marine biodiversity, coral and deep-sea ecosystems.

Some topics, such as sea-level rise or the long-term consequences of climate change on the ocean, draw on one or several articles published this year. They are thus deliberately short, as to draw attention to the key facts available to us today.

Others, like ocean circulation or coral bleaching summarize in depth the available data and models.

Yet other articles further examine emerging topics, such as the role of marine protected areas in climate change, human migrations, national contributions of the Mediterranean basin, or more broadly international law.

This set of articles owes a great deal to the work of the Platform's scientific council, but also to the work of the young scientists group, initiated by FACT-O (French American Climate Talks on Ocean), who wrote or took part in the writing of nearly half of these productions.

FACT-O is a series of public conferences programmed over 2 years (2016 and 2017) in North America, during which leading scientists, civil society representatives, NGOs, political figures, journalists, and entrepreneurs will speak about oceans and the associated issues. It aims at creating a research programme for young scientists to facilitate exchanges between the two countries. The creation of the group "Youth for Oceans!" (YO!), is a declination of this project. It is an interdisciplinary and international group of young scientists seeking to promote knowledge on the links between the ocean and the climate, to encourage a dialogue between science and society, and to advocate a better integration of the ocean in international climate negotiations.

The COP22, which will be held in Marrakech from the 7th to the 18th of November 2016, appears as an opportunity to go from the Agreement to action. Indeed, the Paris Agreement is a key event in the progress of climate negotiations, thanks to the commitments made by a great number of States. This set of articles raises key issues concerning the interactions between the ocean and the climate, and may take part in the implementation of action.

Sea-level is rising

Benoît Meyssignac

For approximately 3 000 years, sea-level had been stable but recent observations indicated an increase in the average speed of sea-level rise, currently at 3.5 millimetres per year. The heat distribution in the climate system causes thermal expansion of oceans, continental glaciers melts and mass loss of ice caps, all evenly contributing to the phenomenon. If these processes intensify, recent estimates suggest a mean sea-level rise of 60 cm to 1 meter by 2100. Sea-level rise significantly varies from one region to another. Moreover, this process is further accentuated when combined with other non-climate factors such as soil compaction or loss of sediment supply by rivers… The impacts of sea-level rise are uncertain in many regions and the use of evolution models to address climate forcing is an important tool to help decision-making in urban planning.

As sea-level stabilised 3000 years ago, at the end of the last glacial period deglaciation, tide gauge observations over the past 150 years indicate that sea-level has once again started to rise during the 20th century. During these last two decades the speed of sea-level rise has practically doubled in comparison to previous decades. It has reached 3.5 millimeters per year on average, which French American altimetric satellite Topex/Poseidon, Jason 1 and Jason 2, observations highlighted. These satellites have been developed by the Centre National d'Études Spatiales and NASA since 1992.

Everything suggests that the current global mean sea-level rise is linked to global warming that has been affecting the planet for several decades, as it is due to ocean thermal expansion and the melting of the continental ice sheet.

Over the second half of the 20th century, the ocean has significantly warmed. It currently stores nearly 90% of excess heat accumulated in the climate system over the course of the past 50 years. Ocean thermal expansion caused by the rise of the sea's temperature explains part of the observed sea-level rise.

A significant decline of the continental ice sheet has occurred in the last few years. Mountain glaciers are melting and peripheral glaciers of Greenland and western Antarctica are flowing directly in the ocean at an accelerated speed. This is another major cause of the current sea-level rise.

For the last two decades, each of these factors (ocean thermal expansion, mountain glacier melts, loss of mass of polar caps), contribute to one third of the observed sea-level rise.

Thanks to their complete coverage of the ocean area, altimetric satellites also show that sea-level rise is far from being the same everywhere. For instance, in the West Pacific, the sea has risen 2 to 3 times faster than the average in the last 20 years. It is now known that this significant regional variability is due to the uneven distribution of heat in the ocean. As a result, the sea-level rises faster in some regions than in others.

Sea-level rise is a serious threat for many low-lying coastal regions, often largely populated. A significant sea-level rise is expected over the course of the 21st century because ocean thermal expansion will continue, and mostly because of the melting continental ice sheet. If Greenland's polar ice caps were to disappear, the sea-level would rise by 7 meters! However if such an event happened, it would take several centuries or even several millennia. It is still unknown what polar ice caps will precisely contribute to sea-level rise in the next decades. However, some recent estimates suggest a mean sea-level rise of 60 cm to 1 meter by 2100, with significant variations from one region to another.

In many low-lying coastal regions, sea-level rise is combined with other non-climate factors. This makes them even more vulnerable. For instance, it is the case of soil compaction due to natural events (for instance, sediment overload in large river deltas) or human activity (underground water or oil pumping).

Other factors, such as loss of sediment supply to the ocean by rivers due to dam constructions, intensive urbanization of coastal areas, variations of coastal currents, etc., also contribute to modifying coastal morphology. For many regions around the world (including France and its overseas departments and territories), the respective contribution of each of these factors to coastal erosion is still uncertain. Evolution and vulnerability models of coastal zones as a response to anthropogenic and climate forcing have become essential decision-making tools to help policy makers in charge of urban planning.

The Long-Term Consequences of Climate Change on Oceans

Xavier Capet

Debates on mitigation and adaptation measures to adopt against climate change are based on observations and estimations over a range of less than 250 years. A recent study by Clark and his collaborators, published in Nature Climate Change, covers extremely long term (over 10,000 years[1]) climate consequences. Their scope is linked to CO_2 emissions. According to these scenarios, the temperature increase could exceed the 2 °C limit, and a 2 to 4 meters per century sea-level rise could be expected in the next millennium. These results confirm the importance of keeping a large quantity of fossil resources untouched.

A recent article published in Nature Climate Change discusses long-term climate impacts of anthropic CO_2 emissions. As did several previous studies, it sheds light on long-lasting effects, over the next 10,000 years at least. The magnitude of these effects will strongly depend on our capacity to leave unused a significant fraction of available fossil resources.

The major part of the political debate regarding mitigation and adaptation measures to take against climate change relies on observations covering the past 150 years, as well as climate projections for the next 85 years. The focus on this timeframe of less than 250 years overshadows some of the key issues linked to climate change.

The 21st century, and maybe the next one, is the period during which the majority of anthropic carbon emissions shall occur. The consequences however will be experienced for numerous millennia. In this study by Clark and his colleagues, consequences of our emissions are considered in the context of long climate timescales, going back 20 millennia (at the end of the last ice age and the start of human civilization), and looking forward over the next 10 millennia, during which expected impacts of anthropic climate change will grow and remain.

The study relies on numerical simulations of atmospheric surface temperature changes and sea-level rise for the next 10,000 years. These simulations highlight very contrasted climate destinies depending on cumulative emissions of CO_2 (carried on during 20th, 21st and possibly 22nd century). Downscaling of these results enables the authors to predict sea-level rise at a regional scale. The study takes into account 4 emissions scenarios, characterised by different cumulative CO_2 emissions into the atmosphere, from a minimum of 1280 PgC to a maximum of 5100 PgC. 1280 PgC means a 15% use of our existing resources. This is about 1.5 times the total quantity of CO_2 emitted since the beginning of industrial revolution. At the current pace of emissions, it would take 70 years to reach this, after which all emissions should cease. 5100 PgC corresponds to approximately 70% to 90% of our current fossil resources.

1 CLARK P. U., SHAKUN J. D., MARCOTT S. A., *et al.*, 2016 – *Consequences of Twenty-First-Century Policy for Multi-Millennial Climate and Sea-Level Change*. Nature Climate Change.

To burn around 5 100 PgC would lead to an increase of temperature far above 2 °C, with a very high probability that this increase would exceed 5 °C for more than 10,000 years. In parallel, a sea-level increase by 2 to 4 meters per century in the next millennium would be expected. In 10,000 years, our emissions would be still responsible for continued sea-level rise, and this level would be 25 to 50 meters above the current one, according to the study. A strong limitation of our total emissions at 1280 PgC would also lead to very long-term consequences but of much reduced magnitude, in particular with respect to increasing global temperatures. The probability to reach beyond the 2 °C limit written down in the Paris Agreement would nonetheless remain high in this scenario and human societies would face a global sea-level rise of about 10 meters. In this reduced emissions scenario, the population currently living in lands to be submerged in the future is estimated to 1.3 billion.

All of these results confirm the importance of efficient action to leave as much of the available fossil fuel as possible underground. Consequences of such actions will be felt for thousands of years. In contrast, even significant reductions of emissions rates with no cap on cumulative emissions will not solve anything in the long run.

These results on CO_2 emissions' long-term effects can be understood if we keep in mind that: *1)* a significant fraction of anthropic CO_2 we emit remains active in the atmosphere for a very long time; *2)* the Earth climate system has a very big inertia (essentially due to the ocean), so that when it is perturbed (by our emissions), it takes numerous millennia to adjust, for instance in terms of temperature. As a result, present and future generations will only endure a tiny part of the consequences of current CO_2 anthropic emissions. The major part of these consequences would be endured by the long line of our descendants for hundreds of generations. The authors recommend not to limit the presentation of climate risks to the next 85 years, in order for decisions and public debates to embrace the very long-term consequences of current emissions.

Ocean Circulation and Climate: an Overview

Bertrand Delorme
and Yassir Eddebbar

Ocean circulation plays a central role in regulating climate and supporting marine life by transporting heat, carbon, oxygen, and nutrients throughout the world's ocean. As human-emitted greenhouse gases continue to accumulate in the atmosphere, the Meridional Overturning Circulation (MOC) plays an increasingly important role in sequestering anthropogenic heat and carbon into the deep ocean, thus modulating the course of climate change. Anthropogenic warming, in turn, can influence global ocean circulation through enhancing ocean stratification by warming and freshening the high latitude upper oceans, rendering it an integral part in understanding and predicting climate over the 21st century. The interactions between the MOC and climate are poorly understood and underscore the need for enhanced observations, improved process understanding, and proper model representation of ocean circulation on several spatial and temporal scales.

The ocean is in perpetual motion. Through its transport of heat, carbon, plankton, nutrients, and oxygen around the world, ocean circulation regulates global climate and maintains primary productivity and marine ecosystems, with widespread implications for global fisheries, tourism, and the shipping industry. Surface and subsurface currents, upwelling, downwelling, surface and internal waves, mixing, eddies, convection, and several other forms of motion act jointly to shape the observed circulation of the world's ocean. Several processes contribute differently and concurrently to this circulation, including, but not limited to, solar heating, tides, winds, the Coriolis effect, and density changes due to variations in temperature and salinity. In this article, we describe some of the major mechanisms driving global ocean circulation with a focus on the MOC, and briefly discuss its importance to the climate system, its current observations, and its projected future in a warming world.

DRIVING MECHANISMS

Global ocean circulation can be divided into two major components: *i)* the fast, wind-driven, upper ocean circulation, and *ii)* the slow, deep ocean circulation. These two components act simultaneously to drive the MOC, the movement of seawater across basins and depths.

As the name suggests, the wind-driven circulation is driven by the prevailing winds, primarily the easterlies in the tropics and the westerlies in the mid-latitudes. As the winds blow above the ocean surface, the upper ocean moves in a balance of frictional and Coriolis forces known as Ekman transport. This mechanism drives a net transport of water that is perpendicular to the wind (to the right in the Northern Hemisphere and left in the Southern Hemisphere). This transport results in areas of divergence and convergence that lead, respectively, to upwelling (*i.e.* upward motion of interior waters) and downwelling (*i.e.* sinking of surface waters). In the equatorial Pacific for instance, the easterlies drive poleward divergence of surface waters that are replenished by upwelling of cold interior waters forming the equatorial "cold tongue". In the Southern Hemisphere, the westerlies drive equatorward Ekman transport and upwelling of deep waters that formed centuries ago (Morrison *et al.*, 2015).

General patterns of the wind-driven circulation are shown in Figure 1 as a series of zonal currents (*e.g.* North Equatorial and South Equatorial currents), eastern boundary currents (*e.g.* California and Chile/ Peru Currents), and western boundary currents (*e.g.* Kuroshio Current and Gulf Stream) that form the subtropical and subpolar gyres. The subtropical gyres are especially important as they transport heat from the equator towards the poles through western boundary currents and ventilate the O_2-depleted interior waters of the low latitudes through subsurface return flow of these surface waters (Duteil *et al.*, 2014). These waters upwell again along the equator, closing the "shallow" overturning cells of the MOC. Through its tight dependence on the fast and rigorous circulation of the atmosphere, the wind-driven circulation dominates the short-scale variability of the upper ocean and is the most energetic component.

The deep circulation, on the other hand, acts on much longer timescales. This component is sometimes referred to as the "thermohaline" circulation, due to its dependence on changes in temperature ("thermo") and salinity ("haline"), both of which regulate the density of seawater. When seawater cools or gets saltier, its density increases and the parcel sinks to depth. This sinking occurs primarily in the high latitudes, where heat loss to the atmosphere and sea ice formation leads to significant changes in temperature and salinity, linking the surface and deep oceans, and setting interior ocean properties along its path.

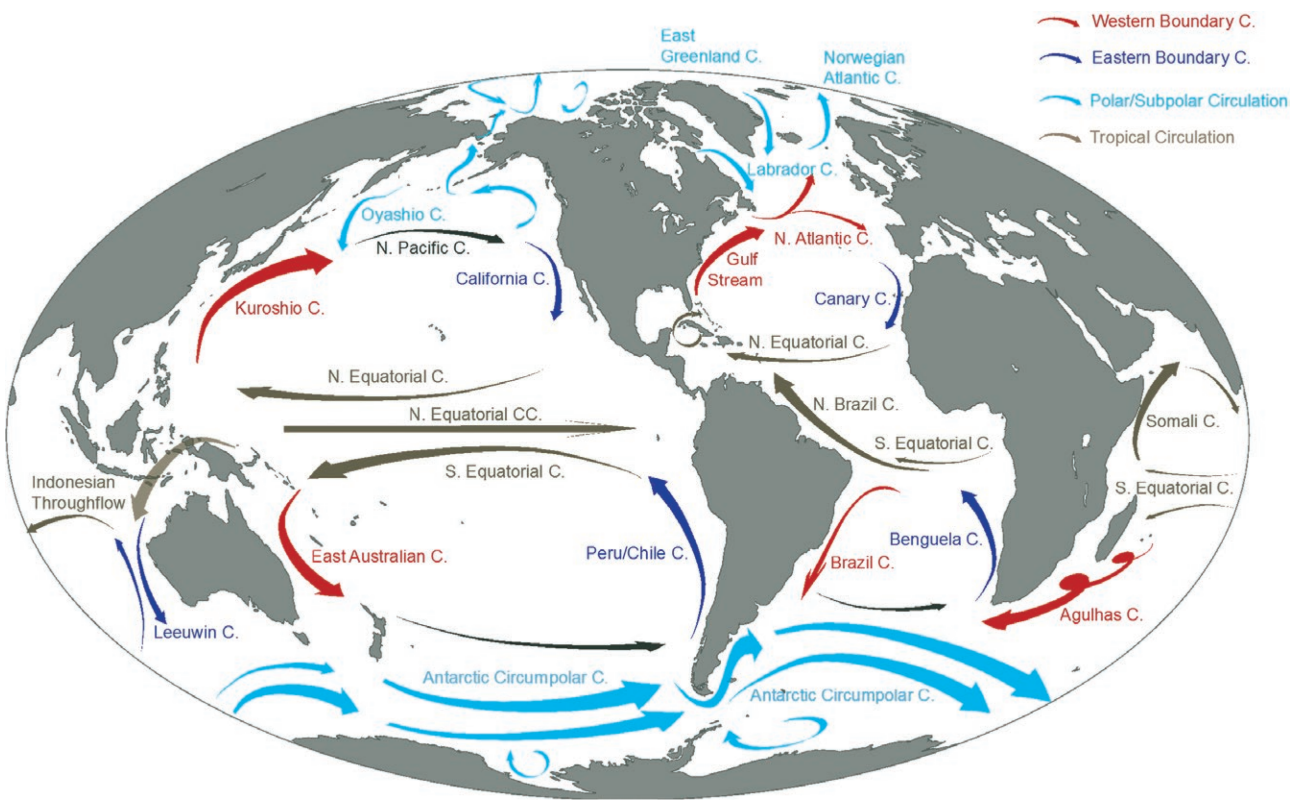

Fig.1 – a) The wind-driven surface ocean circulation. Driven by winds, the surface currents form the main subtropical and subpolar gyres and the tropical/equatorial circulation. Illustration based on wind-driven circulation discussion of Talley *et al.* (2011) and Schmitz (1996). [C. = Current]. © B. Delorme and Y. Eddebbar.

The subpolar North Atlantic is one such important high latitude region, where deep convection and sinking of North Atlantic Deep Water (NADW) occurs as a result of northward transport of heat by the Gulf Stream and subsequent heat loss to the atmosphere (Send and Marshall, 1995). In the Weddell and Ross seas surrounding Antarctica, ice formation over leads (or "Polynyas") and its rejection of brine renders the underlying waters more saline. This process forms a dense water mass known as the Antarctic Bottom Water (AABW), which sinks to the bottom and fills most of the global abyssal ocean (Talley *et al.*, 2011). In contrast, the Indian and Pacific Deep Waters (IDW; PDW) of the Indian and Pacific oceans are formed much more slowly through deep ocean mixing in the low latitudes, and are thus older and richer in carbon and nutrients and depleted in O_2 (Talley, 2013).

The pathway and mechanisms by which this large volume of deep waters returns to the surface, however, have long puzzled oceanographers. Initially, it was thought that dense deep waters upwell back to the upper ocean through widespread vertical mixing, which called for diffusivity on the order of 10^{-4} m^2/s (Munk, 1966). Observations over wide regions however show typically lower values (Lumpkin and Speer, 2007; Ledwell *et al.*, 2011). Thus, recent studies proposed upwelling in the Southern Ocean driven by the westerly winds as the main dynamical return pathway of deep waters to the surface (Toggweiler and Samuels, 1995; Marshall and Speer, 2012). This upwelling links deep waters back to the surface, after which they either sink to the abyss as AABW, or are subducted equatorward through Ekman transport as mode or intermediate waters, to later reach the North Atlantic again, closing the MOC (Marshall and Speer, 2012).

These processes, however, are spatially and mechanistically very complex, and involve both wind-driven and mixing-driven upwelling of NADW, IDW, and PDW across all three basins (Talley, 2013). Deep ocean turbulent mixing is central to these interactions, and is driven by breaking internal waves generated by tidal flow over rough topography as well as winds (Munk and Wunsch, 1998). This mixing

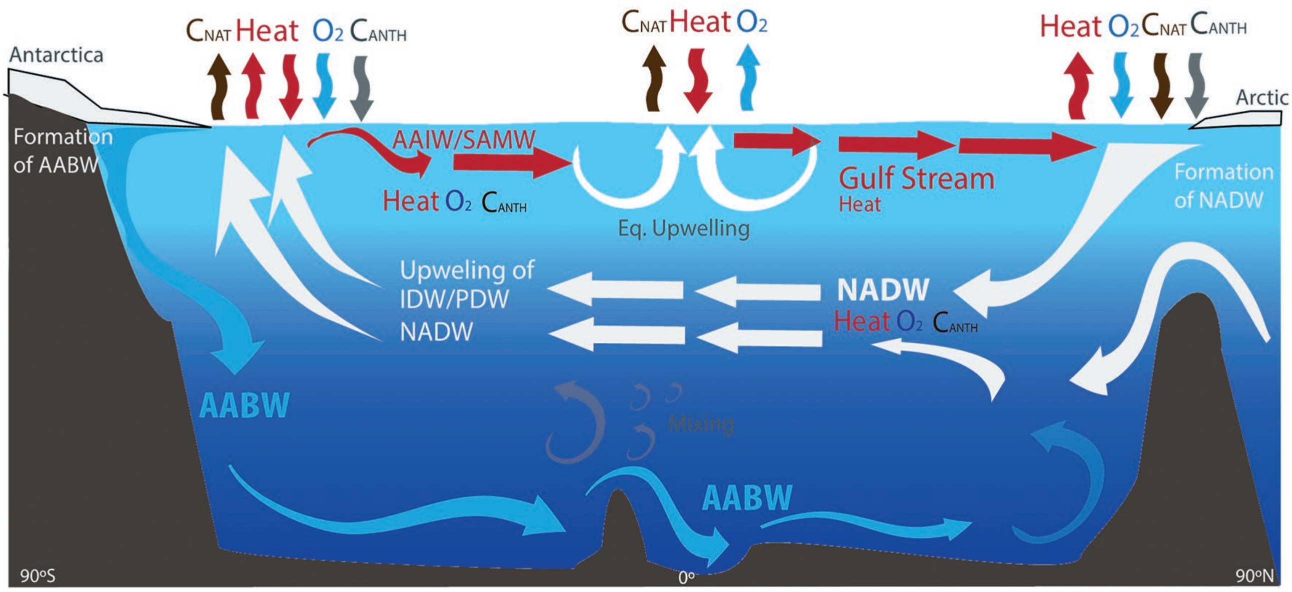

Fig.2 – A simplified 2-d illustration of the Meridional Overturning Circulation and its impact on the mean air-sea flux and transport of heat, oxygen (O_2), anthropogenic (C_{ANTH}) and natural carbon (C_{NAT}). High latitude basins such as the North Atlantic are regions of strong heat loss and uptake of C_{ANTH}, C_{NAT} and O_2. Upwelling in the Southern Ocean leads to simultaneous release of C_{NAT}, uptake of C_{ANTH} and O_2 ventilation as the upwelled deep waters are low in O_2 and rich in Dissolved Inorganic Carbon (DIC). The equatorial zone is a region of intense upwelling of cold, nutrient and DIC-rich waters, driving enhanced uptake of heat, biological production and thermal outgassing of O_2, and strong release of C_{NAT}. [AABW=Antarctic Bottom Water; NADW=North Atlantic Deep Water; IDW=Indian Deep Water; PDW=Pacific Deep Water; AAIW=Antarctic Intermediate Waters; SAMW=Subantarctic Mode Water]. © B. Delorme and Y. Eddebbar.

diffuses surface heat downward to warm and upwell the cold and dense deep waters of the abyss up the water column to reach the Southern Ocean upwelling branch of the MOC. The major role of the Southern Ocean and its complex processes highlight the intertwined nature of the different components of the MOC, which is simplified in an illustration in Figure 2.

OCEAN CIRCULATION: A CLIMATE REGULATOR

Ocean circulation has profound impacts on the mean state and variability of the climate system. Equatorial upwelling and poleward divergence of cold, nutrient and carbon rich waters maintain cool temperatures along the equator, large outgassing of natural carbon and oxygen, biological productivity, and intense heat uptake. The subsequent meridional transport of heat to the poles and its loss to the atmosphere moderates climate in mid-to-high latitude regions (*e.g.* Northwest Europe). Furthermore, changes in equatorial upwelling and currents play central roles in driving *El Niño* and *La Niña* phenomena, thus influencing global climate on interannual to decadal timescales, and modulating the intensity of anthropogenic climate change (Kosaka and Xie, 2016).

Particularly, the MOC alleviates the impacts of climate change by transporting most of the anthropogenic heat to depth (Kostov *et al.*, 2014). Recently, variations in the MOC and its subsequent impacts on ocean heat uptake have been proposed as potential drivers for the "hiatus" in global mean surface warming through the intensification of the shallow overturning cells in the Pacific (Meehl *et al.*, 2011; Balmaseda *et al.*, 2013; England *et al.*, 2014) and through changes in rates of deep water formation in the North Atlantic and upwelling in the Southern Ocean (Chen and Tung, 2014; Drijfhout *et al.*, 2014). Additionally, upwelling of old preindustrial waters that have been isolated from anthropogenic forcing was evoked as a driving mechanism for the surface cooling trends observed over recent decades in the Southern Ocean (Armour *et al.*, 2016).

OCEAN CIRCULATION AND BIOGEOCHEMICAL DYNAMICS

The ocean absorbs over a quarter of anthropogenic CO_2 emissions every year through interactions that involve its complex carbon cycle and circulation (LeQuéré *et al.*, 2013; Stocker *et al.*, 2013). Similarly to heat sequestration, most oceanic carbon uptake occurs at high latitudes. In the North Atlantic, the formation and sinking of NADW act as a gateway for storing anthropogenic carbon at depth. The Southern Ocean is also a major sink of anthropogenic carbon accounting for nearly half the global oceanic uptake (Morrison *et al.*, 2015). Here, upwelling in this region exposes old preindustrial deep waters to high atmospheric CO_2 concentrations. Carbon uptake in this region however reflects a subtle balance between vigorous uptake of anthropogenic carbon and outgassing of natural carbon due to the carbon-rich contents of these upwelled waters. The future of this balance is unclear, requiring deeper understanding of the physical and biogeochemical dynamics that govern the Southern Ocean.

The rate of formation of intermediate and deep water masses in the high latitudes and upwelling in the Southern Ocean also exert major controls on the oceanic O_2 inventory. The poleward transport and subsequent loss of ocean heat to the atmosphere and vertical mixing at high latitudes drives substantial uptake of O_2 (Gruber *et al.*, 2001). The sinking of these waters ventilates the interior ocean where microbial respiration continuously consumes O_2 during the remineralization of sinking organic matter. As the ocean warms, its oxygen content is expected to decline due to reduced gas solubility and weakened ventilation due to surface warming effects on stratification. O_2 decline has been observed in several regions globally, raising serious concerns for marine ecosystems, biogeochemical cycling, and global fisheries (Keeling *et al.*, 2010). The attribution and prediction of ocean oxygen decline however remain challenging due to its tight coupling to ocean circulation and natural variability, which are not well observed or understood.

Changes in ocean circulation are also likely to influence the rate of nutrients supply from depths to the surface.

Again, the Southern Ocean is a major player in this balance, as its upwelling supplies nutrients for 75% of global primary productivity (Morrison *et al.*, 2015). Changes in global ocean circulation thus have major implications for marine primary productivity, the building block of life in the ocean.

OBSERVING OCEAN CIRCULATION: A MAJOR CHALLENGE

Observing ocean circulation is inherently challenging due to its long timescale and large spatial extent (Abraham *et al.*, 2013). Recent observational efforts however have drastically improved our understanding of ocean circulation. Satellite altimetry observations of sea surface height, for instance, have provided powerful insights on surface velocity fields and the spatiotemporal variability of the wind-driven circulation

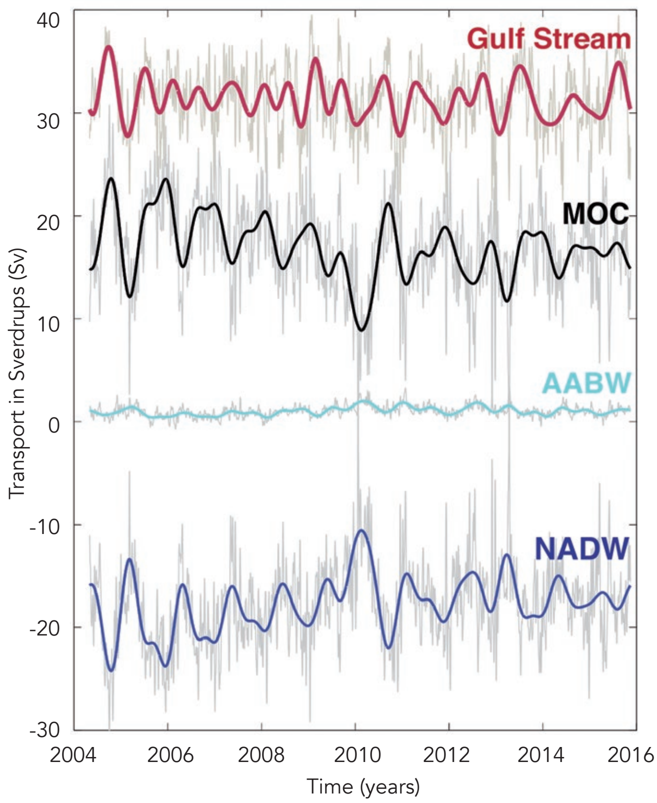

Fig.3 – Timeseries of AMOC and its components at 26.5 °N shown as northward transport in Sverdrups (1 Sverdup=10^6 m^3/s). Bold lines indicate smoothed timeseries using a 6-month low-pass filter. Data obtained from the RAPID/MOCHA array (www.rapid.ac.uk). [AABW=Antarctic Bottom Water (cyan); MOC=net Meridional Overturning Circulation (black); NADW=North Atlantic Deep Water (navy blue); and Gulf Stream (red)]. © B. Delorme and Y. Eddebbar.

(Rhein *et al.*, 2013). The components and structure of the MOC were clearly outlined by hydrographic measurements of temperature, salinity, O_2, nutrients, and other tracers thanks to the World Ocean Circulation Experiment (WOCE) and other hydrographic surveys of the world's ocean. These measurements, though essential for basic understanding of the MOC, provide only a snapshot of the ocean at a specific time and region, and thus significant gaps remain in observing the MOC, including its temporal and spatial variability. Recently, continuous monitoring using 19 moorings located along the 26.5°N latitude of the Atlantic by the RAPID/MOCHA array (Smeed *et al.*, 2016) provided new and unique insights on the Atlantic MOC (AMOC). Figure 3 shows substantial variability in AMOC and its components on monthly to interannual and longer timescales. A markedly steep downward trend from 2006 through 2010, for instance, shows a nearly 50% reduction in amplitude, that was followed by a rapid partial recovery in 2011. Much of this variability arises from changes in the southward transport of NADW at depth, and reflects the influence of high latitude processes where these waters form.

Similarly to other observed regions, no long-term trends have been detected in the MOC intensity so far (Rhein *et al.*, 2013), though observational records are too short to infer long-term changes. The increasing length of continuous timeseries such as the RAPID/MOCHA array are fundamental to assessing secular trends that may be related to anthropogenic warming or natural variability phenomena. Furthermore, the recent advances and expansion of the Argo floats program (Roemmich and Gilson, 2009) is beginning to paint a global 3-dimensional picture of ocean circulation. Together, these observations not only offer a wealth of information for understanding the MOC, but also present a powerful validation test for global climate models (Danabasoglu *et al.*, 2014), an essential task for reliable climate predictions.

THE MOC IN A WARMING WORLD: FUTURE PROJECTIONS

With the accumulation of greenhouse gases in the atmosphere, the MOC is expected to weaken, as warming and ice melt at high latitudes reduces the density of upper ocean waters and thus increases the stratification of the water column. While a collapse of the MOC in the Atlantic is unlikely, climate models predict a 34% weakening of AMOC by 2100 for a high emission (RCP8.5) scenario (Collins *et al.*, 2013). The magnitude of this weakening is not well constrained, ranging from 12-54%, and thus the future of the MOC and its role in transporting anthropogenic heat and carbon from the surface to the deep ocean remains highly uncertain (Stocker, 2013).

In the Southern Ocean, the Antarctic Circumpolar Current is expected to move poleward in the future, as a response to the anticipated poleward contraction and intensification of westerly winds around the Antarctic continent. This displacement is expected to cause enhanced warming between 40°S and 60°S and increased equatorward Ekman transport, increasing the upwelling of relatively warm deep-water masses (Collins *et al.*, 2013). Due to temperature-driven decreases in density, the formation of Antarctic Bottom Water and its northward sinking towards the global abyss is expected to weaken.

Furthermore, as warming dramatically changes the physical landscape of the high latitudes, interactions between polar ice sheets and ocean circulation become increasingly important. This is due to: *(1)* the potential of freshwater input from ice shelf melt to alter the deep branch of the MOC, and *(2)* the influence of subsurface warming on ice shelf melting which may contribute significantly to global sea-level rise (Shepherd *et al.*, 2012). Warming around Antarctica is expected to have a major influence on ice shelves' mass balance through intrusion of warm currents below ice shelves, accelerating basal melt. In these waters, where salinity dominates density, freshwater input forms a thin lid of cold, low-salinity water, which increases stratification and prevents warmer interior waters from reaching the surface (Hansen *et al.*, 2016). The surplus of subsurface heat is hence made available to melt ice shelves, which in turn leads, through a positive feedback, to further melt and stratification. Crevassing due to warming atmospheric temperatures and subsurface warm currents under ice shelves may also drive non-linear responses of ice melt to anthropogenic warming with potential for significant sea-level rise (DeConto and Pollard, 2016). These processes are currently subject to intensive observational and modeling research, and may provide key insights for global climate models that currently do not simulate ocean-ice sheets interactions due to their relatively large resolutions (Winton *et al.*, 2014).

Understanding the past, present, and future of the MOC is crucial to understanding climate change in the 21st century. This is only possible through continuous and expanded monitoring of the MOC, improved process understanding of mechanisms driving ocean circulation and interactions with the cryosphere, and proper representation of these processes in climate models. The MOC's control over global surface temperatures and carbon uptake has major implications for international climate policy, which often relies on these quantities in setting international policy goals (*e.g.* the 2°C target), and should thus be taken into account when designing long-term mitigation and adaptation strategies.

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REFERENCES

- ABRAHAM J. P. *et al.*, 2013 – *A Review of Global Ocean Temperature Observations: Implications for Ocean Heat Content Estimates and Climate Change.* Rev. Geophys., 51, 450–483.
- ARMOUR K.C., MARSHALL J. , SCOTT J., DONOHOE A. and NEWSOM E.R., 2016 – *Southern Ocean Warming Delayed by Circumpolar Upwelling and Equatorward Transport.* Nature Geoscience, 9, 549–554.
- BALMASEDA M. A., TRENBERTH K. E. and KALLENE., 2013 – *Distinctive Climate Signals in Reanalysis of Global Ocean Heat Content.* Geophys. Res. Lett., 40, 1754–1759.
- CHEN X. and TUNG K. K., 2014 – *Varying Planetary Heat Sink Led to Global-Warming Slowdown and Acceleration.* Science, 345, 897–903.
- DANABASOGLU G. *et al.*, 2014 – *North Atlantic simulations in Coordinated Ocean-ice Reference Experiments phase II (CORE-II). Part I: Mean states.* Ocean Modelling, 73, 76-107.
- DECONTO R.M. and POLLARD D., 2016 – *Contribution of Antarctica to Past and Future Sea-Level Rise.* Nature, 531(7596), pp.591–597.
- 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., BLAKERA. 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.* Geophys. Res. Lett., 41, 7868–7874.
- DUTEIL O., BÖNING C. W. and OSCHLIES A., 2014 – *Variability in Subtropical-Tropical Cells Drives Oxygen Levels in the Tropical Pacific Ocean.* Geophysical Research Letters, 41 (24). pp. 8926-8934.
- ENGLAND M. H., MCGREGOR S., SPENCE P., MEEHL G. A., TIMMERMANN A., CAI W., SEN GUPTA A., MCPHADEN M. J., PURICH A. and SANTOSO A., 2014 – *Recent Intensification of Wind-Driven Circulation in the Pacific and the Ongoing Warming Hiatus.* Nature Climate Change, 4, 222-227.
- HANSEN J. *et al.*, 2016 – *Ice Melt, Sea Level Rise and Superstorms: Evidence from Paleoclimate Data, Climate Modeling, and Modern Observations that 2°C Global Warming Could Be Dangerous.* Atmospheric Chemistry and Physics, 16(6), pp. 3761–3812.
- HUGHES G. and GRIFFITHS R., 2005 – *A Simple Convective Model of the Global Overturning Circulation, Including Effects of Entrainment into Sinking Regions.* Ocean Modelling, 12(1-2), pp.46–79.
- KEELING R. F., KORTZINGER A. and GRUBER N., 2010 – *Ocean Deoxygenation in a Warming World.* Annu. Rev. Mar. Sci., 2, 199 – 229.
- KOSAKA Y. and XIE S.-P., 2016 – *The Tropical Pacific As a Key Pacemaker of the Variable Rates of Global Warming.* Nature Geosci., 9.
- KOSTOV Y., ARMOUR K. C. and MARSHALL J., 2014 – *Impact of the Atlantic Meridional Overturning Circulation on Ocean Heat Storage and Transient Climate Change.* Geophys Res. Lett., 41.
- LEDWELL J. R. *et al.*, 2011 – *Diapycnal Mixing in the Antarctic Circumpolar Current.* Journal of Physical Oceanography, 41, pp. 241–246.
- LEQUÉRÉ C. *et al.*, 2013 – *The Global Carbon Budget 1959-2011.* Earth System Science Data, 5(1), pp.165–185.
- LUMPKIN R. and SPEER K., 2007 – *Global Ocean Meridional Overturning.* J. Phys. Oceanogr., 37, 2550–2562.
- MARSHALL J. and SPEER K., 2012 – *Closure of the Meridional Overturning Circulation Through Southern Ocean Upwelling.* Nature Geoscience, 5(3), pp.171–180.
- MEEHL G. A., ARBLASTER J. M., FASULLO J. T., HU A. and TRENBERTH K. E. , 2011 – *Model-Based Evidence of Deep-Ocean Heat Uptake During Surface-Temperature Hiatus Periods.* Nature Climate Change.
- MORRISON A. K., FRÖLICHER T. L. and SARMIENTO J. L., 2015 – *Upwelling in the Southern Ocean.* Physics Today, 68(1), 27-32. Munk, W., 1966. Abyssal Recipes, Deep-Sea Res., 13, pp. 707–730.
- MUNK W. and WUNSCH C., 1998 – *Abyssal Recipes Ii: Energetics of Tidal and Wind Mixing.* Deep-Sea Res., 145, pp.1970–2010.

- ROEMMICH D. and GILSON J., 2009 – *The 2004-2008 Mean and Annual Cycle of Temperature, Salinity, and Steric Height in the Global Ocean from the Argo Program.* Progress in Oceanography. 82:81-100.
- 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 [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- SEND U. and MARSHALL J., 1995 – *Integral Effects of Deep Convection.* J. Phys. Oceanogr., 25, pp. 855–872.
- SHEPHERD A. *et al.*, 2012 – *A Reconciled Estimate of Ice-Sheet Mass Balance.* Science, 338, pp.1183–1189.
- SMEED D., MCCARTHY G., RAYNER D., MOAT B. I., JOHNS W. E., BARINGER M. O. and MEINEN C. S., 2016 – *Atlantic Meridional Overturning Circulation Observed by the RAPID-MOCHA-WBTS (RAPID-Meridional Overturning Circulation and Heatflux Array-Western Boundary Time Series) Array at 26N from 2004 to 2015.* British Oceanographic Data Centre - Natural Environment Research Council, UK.
- STOCKER T. F. *et al.*, 2013 – *Technical Summary. In: Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assess- ment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- TALLEY L., 2013 – *Closure of the Global Overturning Circulation rough the Indian, Pacific, and Southern Oceans.* 26(1), pp. 80–97.
- TALLEY L., PICKARD G., EMERY W. and SWIFT J., 2011 – *Descriptive Physical Oceanography: an Introduction.* Sixth Edition. Elsevier, Boston, MA.
- TOGGWEILER J. R. and SAMUELS B., 1995 – *Effect of Drake Passage on the Global Thermohaline Circulation.* Deep-Sea Res. I 42, 477–500.
- WINTON M. *et al.*, 2014 – *Has Coarse Ocean Resolution Biased Simulations of Transient Climate Sensitivity?* Geophysical Research Letters, 41(23), pp. 8522–8529.

The Ocean is Losing its Breath

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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 and nutrient inputs from human sources, such as agriculture and sewage. 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 been 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 and open ocean 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 off-shore regions of the ocean, where oxygen re-supply 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) . Some of this 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. Changing climate is also exacerbating coastal and estuarine hypoxia. 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.

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};

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

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 due to temperature regulation of oxygen solubility. Ocean warming increases density stratification through changes in temperature and salinity (through ice melt and precipitation). Greater stratification 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). Warming also increases organism metabolic demands and remineralization rates, drawing down oxygen levels. In the open ocean, particularly the North Pacific, atmospheric inputs of nitrogen and iron are enhancing primary production; sinking and microbial decay ultimately consumes additional oxygen (Ito *et al.*, 2016). Along eastern boundary continental margins, atmospheric warming creates land-sea temperature differentials that can intensify upwelling, leading to greater nutrient inputs (and associated production and biogeochemical drawdown) as well as upward advection of low-oxygen waters (Bakun, 1990, 2015; Sydeman *et al.*, 2014, Wang *et al.*, 2015). Another source of oxygen consumption in deep margin waters may come from warming-induced dissociation of buried, frozen methane in gas hydrates (Phrampus and Hornbach, 2012). Aerobic oxidation of the methane in the water column will further deplete midwater oxygen levels (Boetius and Wenzhoffer, 2013). There are several areas where climate-altered circulation patterns can intensify hypoxia, by strengthening low oxygen undercurrents or weakening oxygen-carrying currents, (Gilbert *et al.*, 2005, Bograd *et al.*, 2015, Nam *et al.*, 2015), In contrast, predictions of greater incidence and intensity of cyclones and hurricanes will induce mixing, which can ameliorate hypoxia locally (Rabalais *et al.*, 2009). Warming may also extend periods of seasonal hypoxia or lead to earlier onset, and potentially greater incidence of Harmful Algal Blooms (HABS) which also consume oxygen as they decay (Wells *et al.*, 2015).

Several climate changes can exacerbate nutrient inputs, contributing to hypoxia. Indirectly rising sea-level may eliminate wetlands, which remove nutrients from waters flowing to the coastal ocean. Beyond warming, elevated CO_2 levels can alter plant pore function on land, increasing water use efficiency and leaving 3-6 % more water runoff, which accumulates nutrients before entering the ocean (Reay *et al.*, 2009). Increasing precipitation can contribute to hypoxia through intensified nutrient runoff, snow melt, soil erosion, and greater stratification (http://nca2014.globalchange.gov).

The latest research results suggest that the potential expansion of coastal hypoxia and OMZs could have large effects on, *e.g.*, fisheries species through habitat compression, altered food webs, and modified species interactions, including with fishermen. Contraction of habitat and of species' ranges are predicted to result from the combined effects of warming and deoxygenation on the metabolic index of fish and invertebrates (Deutsch *et al.*, 205). Even at non-lethal levels, exposure to low dissolved oxygen concentrations can result in reduced growth and reproduction, body size, as well as altered behaviours and distributions of marine species (Cheung *et al.*, 2013). 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 loses its breath locally the global ecosystem service of providing an environment conducive to life is hampered.

Over larger scales, global syntheses of oxygen data show hypoxic waters have expanded by 4.5 km^2 at 200 m (Stramma *et al.*, 2010) with widespread loss in the southern ocean (Helm *et al.*, 2011), W. Pacific (Takatani *et al.*, 2012), and N. Atlantic (Stendaro and Gruber, 2012). Overall oxygen declines have been greater in the coastal than the open ocean (Gilbert *et al.*, 2010) and often greater inshore than offshore (Bograd *et al.*, 2015).

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). Recent efforts have modelled deoxygenation against a backdrop of natural variability to predict the time of emergence of the deoxygenation signal in the global oceans (Fig. 3; Long *et al.*, 2016). 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).

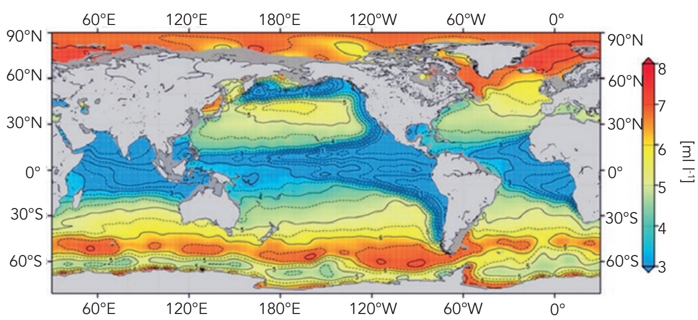

Fig.2 — Annual average oxygen concentration [ml l^{-1}] at 200 m depth (one-degree grid, contour interval 0.5 ml l^{-1}) (World Ocean Atlas 2013, Garcia *et al.*, 2014).

STRATEGIES FOR THE FUTURE

Deoxygenation, along with ocean warming and ocean acidification form a deadly trio of threats to ocean life from shallow water to the deep ocean (Gattusso *et al.*, 2015; Levin and LeBris, 2015). 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). Multiple approaches, including use of natural gradients, 88 historical data, geochemical proxies, and laboratory experiments are needed to better understand how oxygen interacts with other stressors interact to shape ecosystem structure and influence function (Breitburg *et al.*, 2015; Sperling *et al.*, 2016). 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 coastal and open ocean is projected to grow by 50 percent by 2050 (Noone *et al.*, 2012), leading to the increased frequency, intensity and duration of hypoxia (Ito *et al.*, 2016). At the same time intensifying upwelling winds (Wang *et al.*, 2015) are projected to bring 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 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 of dead zones. However, marine sediments introduce a delay in recovery. Due to the

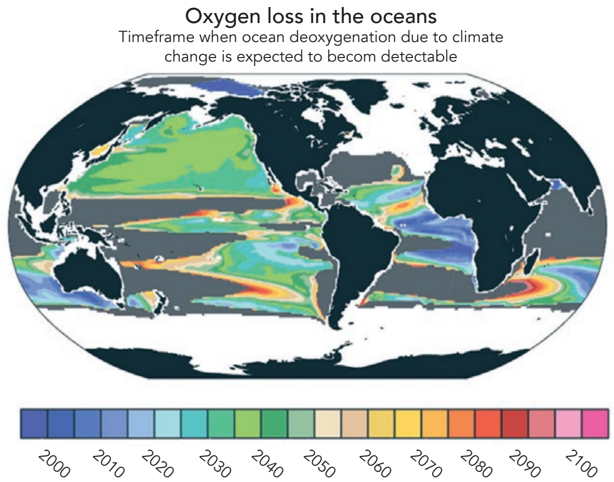

Fig.3 — Time of emergence of the ocean deoxygenation signal against a backdrop of variability (from Long *et al.*, 2016).

non-linearity of marine processes this 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 'hot spots', *e.g.* the Eastern Boundary Upwelling Regions. In addition to these regional 'hot spots', 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.
- BAKUN A., BLACK B.A., BOGRAD S.J., GARCIA-REYES M., MILLER A.J., RYKACZEWSKI R.R. and SYDEMAN W.J., 2015 – *Anticipated Effects of Climate Change on Coastal Upwelling Ecosystems.* Current Climate Change Reports 2, 85-93.
- BOETIUS A. and WENZHÖFER F., 2013 – *Seafloor Oxygen Consumption Fueled by Methane From Cold Seeps.* Nature Geoscience doi:10.1038/ngeo1926.
- 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.
- BREITBURG D.L., SALISBURY J., BERNHARD J.M., CAI W.J., DUPONT S., DONEY S., KROEKER K., LEVIN L.A., LONG C., MILKE L.M., MILLER S.H., PHELAN B., PASSOW U., SEIBEL B.A., TODGHAM A.E. and TARRANT A., 2015 – *And on Top of All That... Coping with Ocean Acidification in the Midst of Many Stressors.* Oceanography 28: 48-61 (2015)
- 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.
- CHEUNG W.L. *et al.* – *Shrinking of Fishes Exacerbates Impacts of Global Ocean Changes on Marine Ecosystems.* Nature Climate Change 3, DOI: 10.1038/NCLIMATE1691.
- DEUTSCH C., FERREL A., SEIBEL B., PORTNER H.O. and HUEY R.B., 2015 – *Climate Change Tightens a Metabolic Constraint on Marine Habitats.* Science 348, 1132-1145.
- 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.
- GATTUSO J.P. *et al.* – *Contrasting Futures for Ocean and Society from Different Anthropogenic CO_2 Emissions Scenarios.* Science 349, DOI: 10.1126/science.aac4722.
- GILBERT D., SUNDBY B., GOBEIL C., MUCCI A. and TREMBLAY G.H., 2005 – *A Seventy-Two Year Record of Diminishing Deep-Water Oxygen in the St. Lawrence Estuary: the Northwest Atlantic Connection.* Limnol. Oceanography, 50, pp. 1654-66.
- GILBERT D., RABALAIS N.N., DIAZ R.J. and ZHANG J. – *Evidence for Greater Oxygen Decline Rates in the Coastal Ocean than in the Open Ocean.* Biogeosciences, 7, pp. 2283-2296.
- 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.
- 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.
- HELM K.P., BINDOFF N.L. and CHURCH J.A., 2011 – *Observed Decreases in Oxygen Content of the Global Ocean.* Geophys. Res. Lett. 38, DOI: 10.1029/2011GL049513.
- 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.
- ITO T., NENES A., JOHNSON M.S., MESKHIDZE M. and DEUTSCH C., 2016 – *Acceleration of Oxygen Decline in the Tropical Pacific over the Past Decades by Aerosol Pollutants.* Nature Geoscience 9, 443-447.
- 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. and 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.
- LEVIN L.A. and LE BRIS N., 2015 – *Deep Oceans under Climate Change.* Science 350: 766-768.
- LONG M.C., DEUTSCH, C. and ITO T., 2016 – *Finding Forced Trends in Oceanic Oxygen.* Global Biogeochem. Cycles, 30, pp. 381–397.
- MATEAR R.J., HIRST A.C. and 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.
- REAY D.S., DENTENER F., SMITH P., GRACE J. and FEELY R., 2015 – *Global Nitrogen Deposition and Carbon Sinks.* Nature Geosciences, 1, pp. 430-37.
- 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.
- SPERLING E.A., FRIEDER C.A. and LEVIN L.A – *Biodiversity Response to Natural Gradients of Multiple Stressors on Continental Margins*. Proceeding Royal Society B. 283: 20160637
- 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.
- STENDARDO I. and GRUBER N., 2012 – *Oxygen Trends Over Five Decades in the North Atlantic*. J. Geophys. Res., 117, doi:10.1029/2012JC007909.
- SYDEMAN W.J., GARCÍA-REYES M., SCHOEMAN D.S., RYKACZEWSKI R.R., THOMPSON S.A., BLACK B.A. and BOGRAD S.J., 2014 – *Climate Change and Wind Intensification in Coastal Upwelling Ecosystems.* Science, 345 (6192), 77-80.
- TAKATANI Y., SASANO D., NAKANO T. and MIDORIKAWA T., 2012 – *Decrease of Dissolved Oxygen After the Mid-1980S in the Western North Pacific Subtropical Gyre Along the 137°E Repeat Section*. Global Biogeochemical cycles 26, GB2013, doi:10.1029/2011GB004227.
- 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.
- WELLS M.L. *et al.*, 2015 – *Harmful Algal Blooms and Climate Change: Learning from the Past and Present to Forecast the Future*. Harmful Algae 49 (2015) 68–93.
- WORLD RESOURCES INSTITUTE – www.wri.org/our-work/project/eutrophication-and-hypoxia/interactive-map-eutrophication-hypoxia.

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 micro-organisms, 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, which leads us rather to think in terms of global ocean. 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; consequently the ocean is a very stable milieu.

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, and some recently discovered in Greenland (3700 Ma)) are very valuable because they contain within their silicified parts the oldest fossils of known micro-organisms – cyanobacteria. These cyanobacteria began to conquer the ocean from 3,700 to 3,200 Ma when there was no atmospheric oxygen. Thanks to their specific pigments, these cells, when exposed to water, have developed photosynthesis which

1 Practical salinity unit

produces oxygen and sugar by using light and carbon dioxyde (CO_2) before 3500 Ma.

Oxygen then began diffusing beyond 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. This gave life a way out of the ocean.

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 210 Ma, 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 history.

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 270,000. 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 provided us, in 2015, with some very valuable information on the profusion and variety of viruses, bacteria and protists, in particular dinoflagellates. These protists could represent nearly one million species. For all prokaryotes and very small eukaryotes, molecularapproaches (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, salinity, temperature, hydrostatic pressures of the depths and 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 450 Ma for complex metazoans). The great Permian-Triassic extinction played a key role, with 96% extinction of species, both marine and on land (around 251 Ma). The explosion of flowering plant species, insects, and many other groups on Earth (around 130-110 Ma) was decisive after the initial radiations (explosions in species from a single ancestor) beginning in the Devonian and especially the Carboniferous. Co-evolution 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, 11.5 Mt for continental fisheries, 19 Mt for algae (including only 1 Mt for harvesting at sea), and 65.6 Mt for aquaculture (including 20.3 Mt at sea). The grand total – for all groups and all aquatic environments – was about 176 Mt. As a response to water mass warming, halieutic stocks swim up in average 72 kms to the North every ten years in the Northern hemisphere. Overfishing is also worrisome: in 15 years, between 50 to 90% of all large pelagic fish individuals were eliminated! Around three quarters of the stocks are fully or over-exploited

(29%). Aquaculture is booming but this raises questions on environmental impacts, species transplants and - for certain types of activity - the use of animal protein to feed species of interest (they are carnivorous). The living ocean is not only these 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 (93%) 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 (26%), 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. This pollution is massive and widespread worldwide as humans are able to contaminate unoccupied areas (Arctic and Antarctica)! Plastic microbeads have accumulated, under the influence of ocean gyres in gigantic concentrations in five areas of the global ocean. Contaminated effluents should no longer reach the sea!

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). It is also very important to legislate cleverly before any deep mineral exploitation, the deep sea being particularly fragile due to its stability on the very-long term.

This is a lot for the ocean to handle, and it is high time we took action !

Denis Allemand

Coral Reefs and Climate Change

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 microalga, 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 284,300 km² (Smith, 1978) and 617,000 km² (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 55,557 km².

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 4 kg 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 35 kg $CaCO_3$/m²/year (Barnes & Chalker, 1990), *i.e.* a vertical annual growth rate of 1 to more than 10 cm. 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 15 cm per year of axial growth in their natural environment (Dullo, 2005). The size of certain massive corals may even exceed 6 m in diameter.

The success rate 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 dino agellates 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). To this day, 9 clades of zooxanthellae, that are potentially different species, exist (Pochon & Gates 2010). Each one presents unique characteristics, which suggests that they could condition the adaptation of corals to a given environment. 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 30 m depth). By means of modern sequencing techniques, a large diversity in bacteria has been identi ed inside corals. These bacteria appear to play an important physiological role. The entire community of these living organisms forms a functional unit called aholobiont, 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 calci cation of coral by a factor reaching 127 in comparison to night calci cation. 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 and budding. 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 20,000 m^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, over-fishing, 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. 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, 81 pages.
- 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, VA, USA. 23 pages.
- 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.
- DUBINSKY Z. and STAMBLER N., 2011 – *Coral Reefs : an Ecosystem in Transition*. Springer. 552 p.
- 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 DUBINSKY Z. and STAMBLER N. (eds), *Coral Reefs : an Ecosystem in Transition*, Springer Netherlands, pp. 151-176.
- FABRICIUS K. E., LANGDON C., UTHICKE S., HUMPHREY C., NOONAN S. *et al.*, 2011 – *Losers and Winners in Coral Reefs Acclimatized to Elevated Carbon Dioxide Concentrations*. Nature Clim Change 1 : 165-169.
- 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*. In DUBINSKY Z. and STAMBLER N. (eds), *Coral Reefs : an Ecosystem in Transition*. Springer Netherlands, pp. 187-195.
- GARCIA S. M. and DE LEIVA MORENO J. I., 2003 – *Global Overview of Marine Fisheries*. In SINCLAIR M. and VALDIMARSSON G. (eds), *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.
- GATTUSO J.-P. and HANSSON L., 2011 – *Ocean Acidification*. Oxford University Press. 326 p.
- GOLDBERG W. M., 2013 – *The Biology of Reefs and Reef Organisms*. The University of Chicago Press. 401 p.

- 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 ($\Delta^{13}C$ and ^{15}N) of Organic Matrix from Coral Skeleton.* Proc Natl Acad Sci USA 102 : 1525-1530.
- PÊCHEUX M., 2013 – *Review on Coral Reef Bleaching*. Edilivre, 291 p.
- POCHON X. and GATES R. D., 2010 – *A New Symbiodinium Clade (Dinophyceae) from Soritid Foraminifera in Hawaii*. Molecular Phylogenetics & Evolution, 56 : 492 – 497.
- PORTER J. W. and TOUGAS J. I., 2001 – *Reef Ecosystems : Threats to their Biodiversity. In Encyclopedia of Biodiversity.* San Diego : Academic Press, pp. 73-95.
- 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.
- RIEGL B. M., PURKIS S. J., AL-CIBAHY A. S., ABDEL-MOATI M. A. and HOEGH-GULDBERG O., 2011 – *Present Limits to Heat-Adaptability in Corals and Population-Level Responses to Climate Extremes.* PloS one. 6 (9) : e24802.
- ROBERTS J. M., WHEELER A., FREIWALD A. and CAIRNS S., 2009 – *Cold-Water Corals : the Biology of Deep-Sea Coral Habitats.* Cambridge University Press, 334 p.
- SHAMBERGER K. E. F., COHEN A. L., GOLBUU Y., MCCORKLE D. C., LENTZ S. J. and BARKLEY H. C., 2014 – *Diverse Coral Communities in Naturally Acidified Waters of a Western Pacific Reef.* Geophys. Res. Lett., 41, doi : 10.1002/2013GL058489.
- SHEPPARD C. R. C., DAVY S. K., PILING G. M., 2009 – *The Biology of Coral Reefs.* Oxford University Press, 339 p.
- SMITH S. V. and KINSEY D. W., 1976 – *Calcium Carbonate Production, Coral Reef Growth, and Sea Level Change*. Science 194 : 937-939.
- SPALDING M. D., RAVILIOUS C. and GREEN E. P., 2001 – *World Atlas of Coral Reefs.* University of California Press, Berkeley, Los Angeles, London. 424 p.
- TAMBUTTÉ S., TAMBUTTÉ É., ZOCCOLA D. and ALLEMAND D., 2008 – *Organic Matrix and Biomineralization of Scleractinian Corals. In Handbook of Biomineralization.* In BÄUERLEIN E. (ed), *Handbook of Biomineralization*, Wiley-VCH Verlag GmbH. pp. 243-259.
- 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.
- TEEB, 2010 – *The Economics of Ecosystems and Biodiversity Ecological and Economic Foundations.* Pushpam Kumar, Earthscan, London and Washington.
- 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.
- VERON J. E. N., 1995 – *Corals in Space and Time. The Biogeography & Evolution of the Scleractinia.* Australian Institute of Marine Science.
- VERON J. E. N., 2008 – *A Reef in Time. The Great Barrier Reef from Beginning to End.* The Belknap Press of Harvard University Press, Cambridge, Massachusetts, London, England. 289 p.

- 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.
- WILKINSON C., 2008 – *Status of Coral Reefs of the World : 2008.* Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, Australia, 296 p.

Coral Bleaching, an Imminent Threat to Marine Biodiversity

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For thirty years, the ocean mean temperature has been incessantly increasing, which reinforces the intensity and length of coral bleaching. From 2014 to 2016, following an unusual increase in ocean water temperature notably reinforced by a rather marked El Niño phenomenon, scientists observed an exceptionally intense and major bleaching event which could extend beyond 2017. Climate models expect a temperature increase of surface waters from 1 to 3 °C by the end of the 21st century, which threatens the survival of coral reefs around the world beyond the year 2050. The resilience level remains low and limited; the stress coral reefs endure is emphasized by other anthropogenic factors (acidification, sea-level rise, overexploitation, pollution…). In order to protect this natural heritage, which over 500 million people depend upon around the world, it is necessary for governments to take action, beyond local measures, towards reducing human impacts on climate.

Despite their ecological and economic importance, coral reefs are affected by many stress factors at both a local level (overexploitation, destructive fishery techniques, tourism pressure, marine pollution, and coastal development) and at a global level with, for instance, increasing temperature of surface waters and ocean acidification. Anthropogenic pressure and climate change currently threaten most reef ecosystems around the world. Over time, these stress factors can lead to a rupture between the coral host and its photosynthetic symbiotes, a phenomenon called "bleaching" which is, as the name suggests, a lack of color or bleaching of the organism (loss of symbiotes and/or associate photosynthetic pigments) over a more less long period of time.

A moderate decrease in symbiotes and/or associate photo pigment concentration is due to a seasonal and natural phenomenon. This occurs when surface water temperature exceeds seasonal mean maximum temperature over a short period of time which varies according to observed sites. However, for thirty years, the ocean mean temperature has been steadily increasing, due to global warming, reinforcing the intensity and length of the phenomenon scientists define as "bleaching", which now affects reef areas around the world, from the Pacific to the Indian Ocean, including the Caribbean and Red Sea.

BLEACHING: A RECURRENT PHENOMENON IN HISTORY

The first coral bleaching episode was seemingly reported by Yonge and Nicholls regarding the Great Barrier Reef in March 1929, when surface water temperature had reached 35 °C, but it is not until the 1980s that the frequency, intensity and expansion of bleaching episodes increased around the world. This is caused by a "record" increase of ocean surface water temperature due to climate change, combined with the reinforcement of the El Niño phenomenon. Two major bleaching events were reported in 1998 and 2010. The 1998 episode involved 60 island states and nations across the Pacific Ocean, the Indian Ocean , the Atlantic Ocean (Caribbean), the Persian Gulf and the Red Sea.

The areas covering the Indian Ocean were particularly affected, with over 70% of mortality observed over a gradient depth up to 50m. Significant ocean surface water temperature irregularity caused a loss of over 16% of coral reefs around the world. In fact, 1998 was the first "global bleaching episode" declared by the National Oceanic and Atmospheric Administration (NOAA). Again, in 2010, an intense El Niño phenomenon triggered extreme coral bleaching, affecting all reefs throughout the world with, in some regions such as South East Asia, greater consequences in terms of expansion and mortality.

2014-2016: AN EXCEPTIONALLY INTENSE AND MAJOR EVENT

The current bleaching event, spreading over three major ocean basins (Pacific, Atlantic and Indian) is caused by the combined effect of an unusual rise of ocean water temperature, emphasized by global warming, and a particularly marked El Niño phenomenon, described as one of the most intense ever observed. This exceptional bleaching event began in June 2014 in the West Pacific, near Guam and the Mariana Islands and spread to the Hawaiian coasts. It then propagated to the South Pacific, affecting British territories in the Indian Ocean, the Caribbean, and the Florida Keys, covering Cuba, the Dominican Republic and the Marshall Islands.

In October 2015, NOAA officially announced an ongoing 3rd global bleaching event in the three principal ocean basins, threatening 95% of American coral reefs. By the end of 2015, 32% of world reefs had been exposed to a temperature irregularity of 4°C, causing mortality on more than 12 000 km^2. The beginning of 2016 was marked by the propagation of the phenomenon in the South Pacific as well as along the Great Barrier Reef and the Australian West Coast.

During March 2016, the ocean water mean temperature was over 1.5 to 2°C compared to measurements registered between 1971 and 2000 in the Northern area of the Great Barrier, at the same time of the year. Aerial and underwater survey programs showed that out of a total of 911 individual reefs observed on the Great Barrier, 93% were affected and in particular, the 1000km coastal area along the North of Port Douglas, yet considered until then as perfectly protected because the area is isolated from human activity.

"*We had never seen such a large scale bleaching phenomenon until now. The Northern area of the Great Barrier Reef looks as if 10 hurricanes had occurred at the same time*" stated Professor Terry Hughes , Director of the Australian Institute of Marine Science (AIMS). Large hundred-year-old colonies are dying, showing the exceptional nature of this phenomenon. Again, in the Pacific, severe bleaching event were reported in New Caledonia, Fiji Islands and Kiribati, where the mortality rate has reached 80% (Eakin, 2016, person comm, 8th of April). The event is gradually spreading to the West Indian Ocean, the Maldives, Kenya and the Seychelles, with particularly severe consequences in the Coral Triangle area, in Indonesia. Significant temperature irregularities were also registered in the Middle East: the Persian Gulf, the Gulf of Aqaba, and the Gulf of Suez are ranked at a level 2 alert (associated with bleaching and significant and widespread mortality events), while the Gulf of Oman and the Red Sea Reef area attached to Egypt remain at a level 1 alert (associated with bleaching and significant mortality events). Other bleaching events are expected in Japan and the Caribbean during the summer of 2016. NOAA scientists have suggested that global bleaching observed could extend beyond 2017.

THE FUTURE OF CORAL REEFS: BETWEEN HOPE AND CONCERN

In 2015, the mean temperature of ocean surface waters was 0.74°C above 20th Century average temperatures, exceeding by 0.11°C the record for 2014. Climate models expect a temperature increase of surface waters of 1 to 3°C between now and the end of the 21st century. In fact, until recently temperatures only rarely and punctually exceeded the thermo tolerance limit, which causes coral to bleach. However scientists expect this phenomenon to occur on an annual or bi annual basis, thus threatening the survival of coral reefs around the world by 2050. Consequences are alarming because an increase in bleaching frequency, such as that observed in the Caribbean (1995, 1998, 2005 and 2010) for instance, limits ecosystem resilience periods and can cause, in the long term, higher mortality rates. Recent studies have shown coral acclimatization potential to severe temperature anomalies[1]. For instance, certain coral species can modify their symbiotic algae population in order to optimize their resistance to thermal stress or even regulate their genes to reinforce their defense mechanisms. However, this resilience level is rather low and punctual. It is in fact unlikely that it might have a significant role while the ocean temperature steadily rises. Furthermore, the combination with other environmental factors, such as ocean acidification and sea-level rise paired with local threats (overfishing, pollution, physical damage, land erosion, etc.), have to be taken into consideration when predicting the future of coral reefs. The synergetic effect of these stress factors (marine pollution and overfishing) can deteriorate trophic relationships between organisms within the coral reef ecosystem, by stimulating excessive growth of filamentous algae to the detriment of coral which becomes more vulnerable to diseases and infections.

THE NEED FOR AWARENESS

These recent events have raised concern among the scientific community and have sparked awareness of the necessity to act in order to protect coral reefs. New technologies and many resources have been set up in order to follow the geographical spread and evolution of bleaching for a better understanding and apprehension of coral response. For instance, the "Catlin Seaview Survey" Expedition, launched in 2012, created a coral reef monitoring around the world. As a similar action, France is celebrating the 15 year anniversary of the French initiative for coral reefs (Ifrecor). These efforts can lead to the implementation of local actions to reduce human print on reef ecosystems. For instance, Mumby & Harborne (2010) have proved the efficiency of marine protected areas for reef resilience in the Caribbean. Likewise, in 2014, New Caledonia announced the establishment of a "Coral sea natural park", one of the biggest marine protected areas in the world (1.3 million km^2). Biological engineering solutions have been proposed, suggesting the use of "optimized" coral colonies according to new environmental conditions in order to restore deteriorated reefs. Some scientists suggest using "assisted evolution" to modify the coral's resilience limit by performing an in lab artificial selection, consisting in exposing coral to various stress or by selecting thermo tolerant symbiote stem cells.

Local authorities and non-governmental organizations (NGOs) have a crucial role in protecting this heritage, which over 500 million people depend upon. Beyond local actions, governmental decisions have been made to reduce human impact on climate. In December 2015, an international agreement, setting a goal for a global warming limit of 1,5 °C - 2 °C by 2100 was validated by 195 countries (including France) participating in the international climate conference (COP21). In September 2016, China and the USA, two superpowers and major world polluters, ratified this agreement, joining the worldwide common effort. In order to preserve reefs for future generations, we need to propose realistic solutions through unifying programs, addressed to all: decision-makers, industry, general public, youth and directly concerned communities. An efficient protection of biodiversity relies on improving local communities living conditions and their ability to sustainably manage the ecosystem resources which they depend upon[2].

1 https://www.coralcoe.org.au/media-releases/only-7-of-the-great-barrier-reef-has-avoided-coral-bleaching

2 See NGO actions such as Coral Guardian (www.coralguardian.org/association-coral-guardian/).

REFERENCES

- AIMS, 2016 – Western Australian reefs feel the heat from global bleaching event, www.aims.gov.au/docs/media/featured-content.html/-/asset_publisher/Ydk18I5jDwF7/content/western-australian-reefs-feel-the-heat-fromglobal-bleaching-event.
- AINSWORTH T. D. *et al.*, 2016 – *Climate Change Disables Coral Bleaching Protection on the Great Barrier Reef.* Science 352, 338-342 (2016).
- BAHR K. D., JOKIEL P. L. and RODGERS K. S., 2015 – *The 2014 Coral Bleaching And Freshwater Flood Events In Kāne'ohe Bay*, Hawai'i. PeerJ 3, e1136.
- BROWN B., 1997 – *Coral Bleaching : Causes and Consequences.* Coral reefs 16, S129-S138.
- DONNER S. D., SKIRVING W. J., LITTLE C. M., OPPENHEIMER M. and HOEGH-GULDBERG O., 2005 – *Global Assessment of Coral Bleaching and Required Rates of Adaptation under Climate Change.* Global Change Biology 11, 2251-2265.
- EAKIN C. M. *et al.*, 2010 – *Caribbean Corals in Crisis : Record Thermal Stress, Bleaching, and Mortality in 2005.* PloS one 5, e13969.
- FABRICIUS K. E., CSÉKE S., HUMPHREY C. and DE'ATH G., 2013 – *Does Trophic Status Enhance or Reduce the Thermal Tolerance of Scleractinian Corals ? A Review, Experiment and Conceptual Framework.* PloS one 8, e54399 (2013).
- FISCHLIN A. *et al.*, 2007 – *Ecosystems, Their Properties, Goods and Services.*
- FITT W., MCFARLAND F., WARNER M. and CHILCOAT G. – *Seasonal Patterns of Tissue Biomass and Densities of Symbiotic Dinoflagellates in Reef Corals and Relation to Coral Bleaching.* Limnology and oceanography 45, 677-685 (2000).
- GLYNN P., 1993 – *Coral Reef Bleaching : Ecological Perspectives.* Coral reefs 12, 1-17.
- GLYNN P. W., PEREZ M. and GILCHRIST S. L., 1985 – *Lipid Decline in Stressed Corals and their Crustacean Symbionts.* The Biological Bulletin 168, 276-284.
- HERON S. F. *et al.*, 2016 – *Validation of Reef-Scale Thermal Stress Satellite Products for Coral Bleaching Monitoring.* Remote Sensing 8, 59.
- HOEGH-GULDBERG O. and RIDGWAY T., 2016 – *Coral Bleaching Hits Great Barrier Reef As Global Temperatures Soar.* Green Left Weekly, 10.
- HOEGH-GULDBERG O., 1999 – *Climate Change, Coral Bleaching and the Future of the World's Coral Reefs.* Marine and freshwater research 50, 839-866.
- ISRS, 2016 – Reef Encounter, 31.
- JOKIEL P. and COLES S., 1990 – *Response of Hawaiian and Other Indo-Pacific Reef Corals to Elevated Temperature.* Coral reefs 8, 155-162. PALUMBI S. R., BARSHIS D. J., TRAYLOR-KNOWLES N. and BAY R. A., 2014 – *Mechanisms of Reef Coral Resistance to Future Climate Change.* Science 344, 895-898.
- MUMBY P. J. and HARBORNE A. R., 2010 – *Marine Reserves Enhance the Recovery of Corals on Caribbean Reefs.* PLoS ONE 5, e8657, doi : 10.1371/journal.pone.0008657.
- NICHOLLS R. J. *et al.*, 2007 – *Coastal Systems and Low-Lying Areas.*
- NOAA, 2015 – *Noaa Declares Third Ever Global Coral Bleaching Event : Bleaching Intensifies in Hawaii, High Ocean Temperatures Threaten Caribbean Corals.* www.noaanews.noaa.gov/stories2015/100815-noaa-declares-third-ever-global-coralbleaching-event.html.
- NOAA, 2015 – *NOAA Coral Reef Watch : 2015 Annual Summaries of Thermal Conditions Related to Coral Bleaching for NCRMP Jurisdictions.*
- NOAA., 2015 – *State of the Climate : Global Analysis for Annual 2015.* National Centers for Environmental Information, www.ncdc.noaa.gov/sotc/global/201513.
- NORMILE D., 2010 – *Restoration or devastation ?* Science 327, 1568-1570.
- PALUMBI S. R., BARSHIS D. J., TRAYLOR-KNOWLES N. and BAY R. A., 2014 – *Mechanisms of Reef Coral Resistance to Future Climate Change.* Science 344, 895-898.

- Studies, C.C.A.C.o.E.C.R., 2016 – *Only 7 % of the Great Barrier Reef Has Avoided Coral Bleaching.* www.coralcoe.org.au/media-releases/only-7-of-the-greatbarrier-reef-has-avoided-coral-bleaching.
- VAN OPPEN M. J. H., OLIVER J. K., PUTNAM H. M. and GATES R. D., 2015 – *Building Coral Reef Resilience Through Assisted Evolution.* Proceedings of the National Academy of Sciences 112, 2307-2313, doi : 10.1073/pnas.1422301112.
- VEGA THURBER R. L. *et al.*, 2014 – *Chronic Nutrient Enrichment Increases Prevalence and Severity of Coral Disease and Bleaching*. Global change biology 20, 544-554.
- WAKE B., 2016 – *Snapshot : Snow White Coral.* Nature Climate Change 6, 439-439.
- WILKINSON C. R., SOUTER D. N. and NETWORK G. C. R. M., 2008 – *Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005.* Global Coral Reef Monitoring Network.
- YONGE C. M., NICHOLLS A. G. and YONGE M. J., 1931 – *Studies on the Physiology of Corals*. Vol. 1, British Museum.
- ZANEVELD J. R. *et al.*, 2016 – *Overfishing and Nutrient Pollution Interact with Temperature to Disrupt Coral Reefs Down to Microbial Scales*. Nat Commun 7, doi : 10.1038/ncomms11833.

A Case for the Deep Ocean

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Encompassing 95% of the planet's habitable volume, the deep ocean plays a major role in climate regulation, and thus new pressures exerted on it and its components should be a major concern. The deep sea provides many ecosystem services, such as storing heat and anthropogenic carbon emitted into the atmosphere. These services are key to sequestrating CO_2 and CH_4 on longer time-scales, as well as in supporting nutrient cycling on which the entire foodweb (and so commercial activities such as fisheries) relies. Heat absorption and redistribution impacts human exploited-species ranges. Already absorbing many pollutants and waste, the deep ocean could also become a place for new activities such as mining. Setting up key mitigation and adaptation measures to climate change will require new knowledge, and implementation of a complete legal framework and management tools.

Covering over half of the planet, and comprising 95% of its habitable volume, the deep ocean (>200 m) merits dedicated attention in the context of climate change for several major reasons:

- The deep ocean has a predominant role in the sequestration of heat and carbon, with tight links to the upper ocean and atmosphere through vertical mixing, species migrations and particulate sinking, and a diverse range of ecosystems, making it critical to any analysis of ocean roles in climate mitigation and adaptation.
- The deep ocean provides a broad range of ecosystem services that are just beginning to be inventoried; greenhouse gas regulation, support to biodiversity (including genetic diversity), food supply and energy production.
- The deep ocean is increasingly impacted by human activities including contaminant inputs, overfishing, and disturbances from seafloor extractive activities. There is currently little understanding of how these direct impacts will interact with climate stressors.

WE NEED TO INCREASE OUR KNOWLEDGE TO BETTER PROTECT THE DEEP OCEAN

Key adaptations to climate change will require new knowledge, including the broadening of deep-water observation programs, to enable the design of marine protected areas encompassing vulnerable regions in deep waters, and to inform environmental management of industrial activities and development of new policies addressing deep national and international waters.

There is an unprecedented need to integrate the deep ocean into ocean science and policy. Knowledge of deep hydrology, hydrography, pelagic and seafloor ecology is critical to climate predictions and societal impact assessments (*e.g.*, Mora *et al.* 2013) because of the strength of connectivity between the oceans, atmosphere and the terrestrial realm. New international regulations (*e.g.* for mining) and treaties (*e.g.* for biodiversity), environmental management, and spatial planning also must incorporate climate and the role of deep processes.

KEY ELEMENTS TO UNDERSTAND THE FUTURE OF THE DEEP OCEAN

We draw attention to the following themes, which make the case for the significance of the deep ocean.

Ecosystem services of the deep ocean

Life in the deep ocean provides or regulates many valuable services that sustain the planet (Armstrong *et al.* 2012; Thurber *et al.* 2014); key among these are CO_2 and CH_4 sequestration, nutrient cycling, substrate, food and nursery grounds provisioning for fisheries by a variety of habitats. The deep ocean is the largest reservoir of carbon on Earth and constitutes the ultimate sink for most anthropogenic carbon. The biogenic deep-sea carbon component is poorly quantified, but chemosynthetic ecosystems with high carbon fixation rates and vertical transport by pelagic species may significantly contribute to 'blue carbon' sequestration (Marlow *et al.* 2014, Trueman *et al.* 2014, James *et al.* 2016).

Thermal energy budgets

The ocean absorbs 90% of the extra heat trapped by anthropogenic greenhouse gas emissions, with 30% of this being stored at depths >700 m (IPCC 5th assessment report) and is thus a more accurate indicator of planetary warming than surface global mean temperature (Victor and Kennel, 2015). In this stable and mainly cold environment (except in the Mediterranean Sea and at bathyal depths in tropical regions), thermal limits shape species distributions. The consequences of warming on deep ocean waters will profoundly influence ecosystems and their biodiversity. Examples of rapid changes in deep-sea benthic ecosystems have been documented in downwelling, upwelling and polar regions (*e.g.* Danovaro *et al.* 2004, Smith *et al.* 2012, Soltwedel *et al.* 2016), although discriminating natural cycles from climatic impacts in the deep sea will require unprecedented time series data (Smith *et al.* 2013).

Biogeochemical changes

The deep ocean supports major biogeochemical recycling functions; these are expected to undergo major changes. Declines in O_2, pH and aragonite saturation have been observed and are predicted to strongly impact intermediate water depths under future emission scenarios (Bopp *et al.* 2013). Deep-water oxygenation is tightly coupled to the overturning circulation and O_2 trends inform changes in global or basin-scale ocean circulation. As a regulator of the biogeochemical cycling of N, Fe, P, and S, O_2 is key to potential synergistic responses. N_2O production is expected to increase as oxygen declines (Codispoti, 2010), potentially linking O_2 decline and climate through a positive feedback, though large uncertainties remain (Martinez-Rey *et al.* 2015).

Cumulative impacts of changes

There are many climate change-related stressors affecting deep-sea ecosystem functions (Levin and Le Bris 2015). Deep-sea ecosystems may be particularly vulnerable to change due to their environmental stability or to tight links with surface productivity or hydrodynamic regime. Deep-sea diversity patterns are shaped by export production (Woolley *et al.* 2016) and CMIP5 models predict overall decreases in integrated primary productivity with climate change. Large reductions in the tropics and the North Atlantic (Bopp *et al.* 2013), suggest possible negative impacts for deep-sea diversity. We need to assess how and where these cumulative changes, including warming, ocean acidification, aragonite undersaturation, shifts in nutrient fluxes and deoxygenation, will challenge ecosystem stability and species capacity to adapt (Lunden *et al.* 2014, Gori *et al.* 2016). This involves gathering sufficient knowledge about cumulative impacts of multiple stressors to build accurate scenarios of vulnerability.

A need for deep observations

The sparse nature and typically small spatial resolution of deep-ocean observations, combined with overly large spatial resolution of models, results in knowledge gaps and uncertainties. This includes natural variability, the coupling of climate to biogeochemical cycles, and the responses of biodiversity hotspots (*e.g.*, seamounts and canyons). In addition, multicellular life in the deep pelagic realm is still largely unexplored, though this realm represents over 95% of the living space on the planet. Seafloor observatories and long-term time series have started providing insights into how deep-sea ecosystems respond to climate perturbations (Soltweddel *et al*. 2016; Smith *et al*. 2013). Long-term integrated ecological studies, covering a range of deep-sea systems and the most vulnerable hotspots, are needed to identify threats to critical ecosystem services and the potential feedbacks to the climate system and humans.

Synergies of direct human-induced stressors

Beyond the complexity of multiple climate stressors, deep-ocean ecosystems are facing an onslaught from pollutants, fishing, mining, energy extraction, and debris (Mengerink *et al*. 2014), with deep seabed mining now on the near-term horizon. New efforts to develop requirements for environmental impact assessments, environmental indicators, spatial planning and create marine protected areas in deep water will need to incorporate the interplay with climate change.

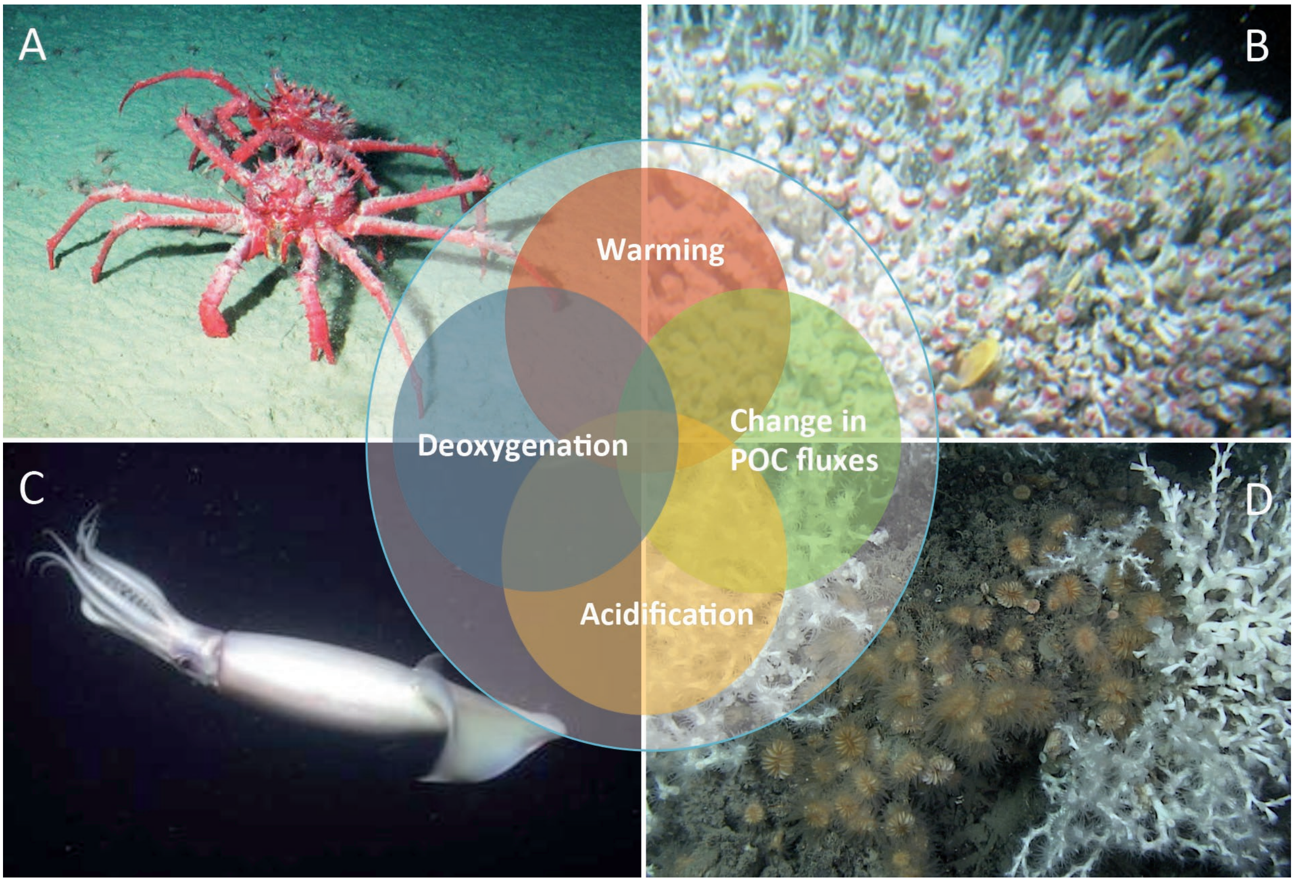

Figure from Levin and Le Bris 2015. Winners and losers from exposure to interacting climate stressors. (A) King crabs invading Palmer Deep in Antarctica enabled by warming (9). (B) Cold seep fauna may expand as warming promotes methane release from the seafloor (12), such as occurs at sites recently discovered along the Atlantic coast. (C) Hypoxia-tolerant Humboldt squid (*Dosidicus gigas*) have extended their distribution in concert with expanding oxygen minima along the East Pacific margin. (D) Cold-water coral reefs vulnerable to warming and acidification in Mediterranean canyons.

[Photo credits: (A) Image courtesy of K. Heirman and C. Smith, NSF LARISSA and Ghent University HOLANT projects. (B) Image courtesy of Deepwater Canyons 2013–Pathways to the Abyss, National Oceanic and Atmospheric Admin- istration (NOAA)–Office of Exploration and Research, Bureau of Ocean Energy Management, and U.S. Geological Survey. (C) Image courtesy of N. Le Bris, Laboratoire d'Ecogéochimie des Environnements Benthiques (LECOB), Fondation Total– UPMC. (D) Image courtesy of R. Starr, NOAA–Cordell Bank National Marine Sanctuary].

REFERENCES

- ARMSTRONG C. W., FOLEY N. S., TINCH R. and VAN DEN HOVE S., 2012 – *Services from the Deep: Steps towards Valuation of Deep Sea Goods and Services.* Ecosyst. Serv., 2, 2–13.
- BOPP L., RESPLANDY L., ORR J. C., DONEY S. C., DUNNE J. P., GEHLEN M., HALLORAN P., HEINZE C., ILYINA T., SEFERIAN R. and TJIPUTRA J., 2013 – *Multiple Stressors of Ocean Ecosystems in the 21St Century: Projections with Cmip5 Models.* Biogeosciences, 10, 6225–6245. doi:10.5194/bg-10-6225-2013.
- DANOVARO R., DELL'ANNO A. and PUSCEDDU A., 2004 – *Biodiversity Response to Climate Change in a Warm Deep Sea: Biodiversity and Climate Change in the Deep Sea.* Ecology Letters 7, 821–828.
- JAMES R.H., BOUSQUET P., BUSSMANN I., HAECKEL M., KIPFER R., LEIFER I., NIEMANN H., OSTROVSKY I., PISKOZUB J., REHDER G., TREUDE T., VIELSTÄDTE L. and GREINERT J., 2016 – *Effects of Climate Change on Methane Emissions from Seafloor Sediments in the Arctic Ocean: a Review: Methane Emissions from Arctic Sediments.* Limnology and Oceanography.
- MARLOW J. J., STEELE J. A., ZIEBIS W., THURBER A. R., LEVIN L. A. and ORPHAN V. J., 2014 – *Carbonate-Hosted Methanotrophy Represents an Unrecognized Methane Sink in the Deep Sea.* Nature Communications 5, 5094.
- GORI A., FERRIER-PAGÈS C., HENNIGE S. J., MURRAY F., ROTTIER C., WICKS L. C. and ROBERTS J. M., 2016 – *Physiological Response of the Cold-Water Coral Desmophyllum Dianthus to Thermal Stress and Ocean Acidification.* PeerJ 4, e1606. doi:10.7717/peerj.1606.
- LUNDEN J. J., MCNICHOLL C. G., SEARS C. R., MORRISON C. L. and CORDES E. E., 2014 – *Acute Survivorship of the Deep-Sea Coral Lophelia Pertusa from the Gulf of Mexico under Acidification, Warming, and Deoxygenation.* Frontiers in Marine Science 1.
- LEVIN L. A. and LE BRIS N., 2015 – *Deep Oceans under Climate Change.* Science 350: 766-768.
- MARTINEZ-RAY J., BOPP L., GEHLEN M., TAGLIABUE A. and GRUBER N., 2015 – *Projections of Oceanic N_20 Emissions in the 21st Century Using yhe IPSL Earth System Model.* Biogeosciences 12, 4133-4148.
- MENGERINK K. J., VAN DOVER C. L., ARDRON J., BAKER M., ESCOBAR-BRIONES E., GJERDE K., KOSLOW J. A., RAMIREZ-LLODRA E., LARA-LOPEZ A., SQUIRES D., SUTTON T., SWEETMAN A. K. and LEVIN L. A., 2014 – *A Call for Deep-Ocean Stewardship.* Science 344: 696-698.
- 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.
- SMITH C. R., GRANGE L. J., HONIG D. L., NAUDTS L., HUBER B., GUIDI L. and DOMACK E., 2011 – *A Large Population of King Crabs in Palmer Deep on the West Antarctic Peninsula Shelf and Potential Invasive Impacts.* Proceedings of the Royal Society of London B: Biological Sciences, rspb20111496. doi: 10.1098/rspb.2011.1496.
- SMITH K. L., RUHL H. A. , KAHRU M., HUFFARD C. L. and A. SHERMAN A., 2013 – *Deep Ocean Communities Impacted by Changing Climate over 24 Y in the Abyssal Northeast.* PNAS 110: 19838-41.
- SOLTWEDEL T., BAUERFEIND E., BERGMANN M., BRACHER A., BUDAEVA N., BUSCH K., CHERKASHEVA A., FAHL K., GRZELAK K., HASEMANN C., JACOB M., KRAFT A., LALANDE C., METFIES K., NÖTHIG E.-M., MEYER K., QUÉRIC N.-V., SCHEWE I., WŁODARSKA-KOWALCZUK M. and KLAGES M., 2016 – *Natural Variability or Anthropogenically-Induced Variation? Insights from 15 Years of Multidisciplinary Observations at the Arctic Marine LTER Site HAUSGARTEN.* Ecological Indicators 65, 89–102.
- THURBER A. R., SWEETMAN A. K., NARAYANASWAMY B. E., JONES D. O. B., INGELS J. and HANSMAN R. L., 2014 – *Ecosystem Function and Services Provided by the Deep Sea.* Biogeosciences 11: 3941-3963.
- TRUEMAN C. N., JOHNSTON G., O'HEA B. and MACKENZIE K. M., 2014 – *Trophic Interactions of Fish Communities at Midwater Depths Enhance Long-Term Carbon Storage and Benthic Production on Continental Slopes.* Proceedings of the Royal Society B: Biological Sciences 281, 20140669–20140669.
- VICTOR D. and KENNEL C., 2014 – *Ditch the 2°C Warming Goal.* Nature 514: 30-31.
- WOOLLEY S. N. C., TITTENSOR D. P., DUNSTAN P. K., GUILLERA-ARROITA G. , LAHOZ-MONFORT J. J., WINTLE B. A., WORM B. and O'HARA T. D., 2016 – *Deep-Sea Diversity Patterns Are Shaped by Energy Availability.* Nature 533: 393-396.

Ecosystem Services of the Deep Ocean

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The concept of ecosystem services (ES) includes the ecological functions and the economic value of ecosystems which contribute to human well-being. This approach is already applied to coastal water management, but it is rarely applied to the deep sea although it represents 97% of the ocean's volume. Deep-sea ES include provisioning services such as fish catch or industrial agents, regulation services such as carbon storage, and cultural services such as inspiration for the arts. However, the deep sea is facing increasing pressures in the form of direct and indirect human activities. This synergy of impacts is widely unknown and the lack of regulation regarding certain parts of the ocean requires great caution.

INTRODUCTION TO ECOSYSTEM SERVICES IN THE DEEP SEA

Ecosystem services (ES) are generally defined as contributions to human well-being from ecosystems (MEA, 2005; TEEB, 2010; Haines-Young and Potschin, 2013). The concept integrates ecological functions and economic values to explain how ecosystem health affects the socio-economic system. ES can be assigned monetary values for use in decision-making, and incorporated into management tools such as marine spatial planning and ecosystem-based management (Jobstvogt *et al.*, 2014). An ES approach has previously been used in terrestrial and shallow water systems (*e.g.*, Seidl *et al.*, 2016; Gunderson *et al.*, 2016), but its application to the deep sea has been extremely limited.

Figure 1 illustrates deep-sea ecosystem services (DSES) that fall into the categories often used to describe ES: provisioning (outputs gained from ecosystems), regulating (regulation of environmental processes), and cultural (non-material benefits). Deep-sea provisioning services include fisheries landings, pharmaceuticals, industrial agents, and biomaterials (Leary, 2004; Mahon *et al.*, 2015). Examples of regulating services are climate regulation, biological controls, and waste absorption (Armstrong *et al.*, 2012; Thurber *et al.*, 2014). There are also cultural services associated with the deep sea, such as educational benefits, aesthetics and inspiration for the arts, the value of knowing a resource exists, and the value of protecting a resource for current and future generations. Many deep-sea functions (*e.g.*, primary biodiversity, element cycling) directly and indirectly contribute to these services, and must also be kept in mind to continue benefitting from DSES. For example, a deep-sea function that supports fisheries is nutrient regeneration (Thurber *et al.*, 2014), which occurs mainly in regions of strong upwelling (*e.g.*, eastern boundary currents, Antarctica), but also in areas where local upwelling can occur (*e.g.*, mesoscale eddies, seamounts). Upwelled nutrients from the deep-sea fuel photosynthesis, which in turn supports major fisheries such as sardines and anchovies.

Increasing human activity in the deep sea has created an urgent need for evaluating impacts on ecosystem health. Anthropogenic carbon dioxide CO_2 emissions have resulted in warming, deoxygenation, and acidification that will change how direct human activity (*e.g.*, fishing, oil and gas drilling, mine tailings placement) impacts deep-sea habitats. In the midst of these cumulative impacts on the deep sea, it is important to consider DSES, how they might be affected, and how to best manage them.

DSES OF CLIMATE REGULATION

The ocean has absorbed approximately one-third of emitted CO_2 (IPCC, 2014) through physical, chemical and biological processes. The deep ocean system serves as a major heat sink and slows down anthropogenic global warming (IPCC, 2014); thus, CO_2 absorbance by the deep sea is a very important climate-regulating service (Thurber *et al.*, 2014). Climate regulation, including carbon sequestration, will continue to be a critically important service provided by the deep sea as CO_2 emissions continue to increase. Warming, deoxygenation, acidification, nutrient changes, and calcium carbonate undersaturation are major ocean climate drivers that will interact with human activities in the deep sea, and future studies need to assess the complex cumulative impacts on deep-sea biodiversity, functioning, and DSES.

Carbon sequestration by the deep ocean is an important climate change mitigation pathway that relies on an efficient "biological pump" (*i.e.*, the physical process of sinking biologically-produced carbon from the upper ocean into the deep sea). The burial of upper ocean-produced carbon in deep sediments contributes to carbon sequestration and climate regulation because it removes the carbon from the atmosphere for thousands to millions of years (Xiao *et al.*, 2010). In addition, this sinking carbon is an important food source for many larger organisms that support deep-sea fishery species. How global climate change affects the biological pump and consequent export and sequestration of carbon to the deep sea remains an important topic of ongoing research (for review, see Turner, 2015), but long-term observations show that trends will vary depending on the region of interest (Levin and Le Bris, 2015).

Greenhouse gases such as methane (CH_4) and CO_2 enter the ocean naturally from deep-seafloor geologic structures such as hydrothermal vents and methane seeps. However, biological fixation of CH_4 and CO_2 by micro- and macroorganisms in these deep-sea ecosystems prevents these gases from entering the water column. This biological filtering of CH_4 and CO_2 at the seafloor is another regulating service and is an important process that indirectly supports commercially fished species (Thurber *et al.*, 2014).

DIRECT HUMAN ACTIVITIES IN THE DEEP

In addition to impacts related to climate, direct human activity in the deep sea is also increasing (Ramirez-Llodra *et al.*, 2011). The deep sea contains a wealth of natural resources and extracting them can be harmful to its many, heterogenous habitats. For example, as global demand and human consumption of fish increase (FAO, 2014), fisheries are moving deeper into the water column and seabed (Watson and Morato, 2013). Trawling disturbs and removes physical structures and sediment on the seabed which can lead to loss of both targeted species and those associated with the seabed (Buhl-Mortensen *et al.*, 2015). In addition, deep-sea fisheries species may take longer to recover because many have longer life spans relative to shallow water species (Norse *et al.*, 2012).

Other extractive activities include oil and gas, and potentially minerals. Oil and gas exploration and drilling are also moving into deeper waters, increasing the risk of oil spills (*e.g.*, Deepwater Horizon; Merrie *et al.*, 2014). Deep-seabed mining regulation under

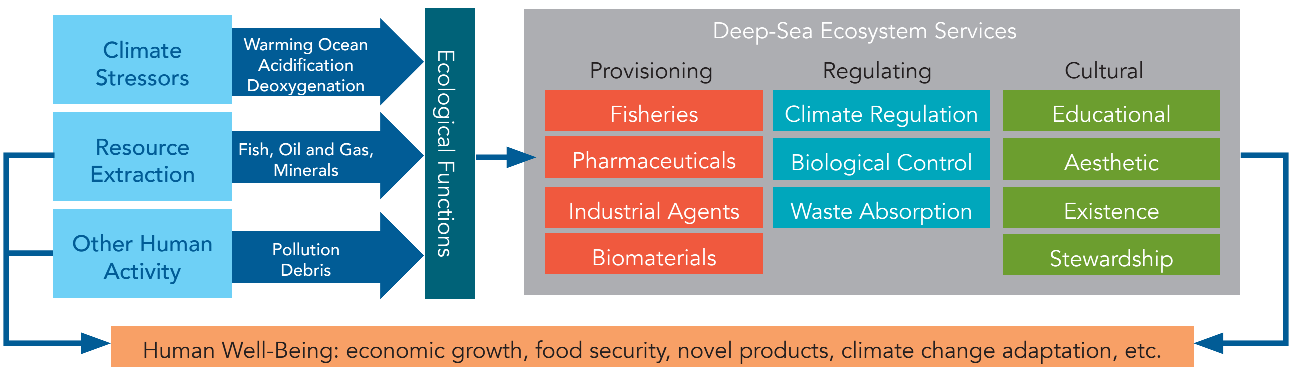

Fig.1 — The relationship among anthropogenic climate change stressors, deep-sea ecosystem services, and human well-being. © J. T. Le and K. N. Sato.

commercial exploitation is currently in development (ISA, 2015). Different mineral deposits of interest are found on hydrothermal vents, seamounts, and abyssal plains, which all host different biological communities that can contribute differentially to DSES. Disturbance of these ecosystems via direct human impacts such as mining, trawling, and other extractive activities (*e.g.*, oil and gas drilling) will likely disrupt this regulatory function with high risk for acute and long-term loss of services.

POTENTIAL IMPACTS OF SYNERGISMS (CLIMATE AND HUMAN ACTIVITIES)

The cumulative impact of multiple climate stressors and extractive activities can lead to additive, antagonistic, or synergistic effects on DSES (Crain *et al.*, 2008). Deep-sea ecosystem functions are not well constrained, nor are the interactions and dynamics between them. This makes it difficult to predict how the provision of DSES will change due to both direct and indirect human impact. This may invoke the precautionary principle (Rio Declaration, 1992), and highlight the need for novel approaches in better understanding the deep sea and the benefits it provides.

The consequences of warming in deep ocean waters will not only influence the regulatory service the deep sea provides as a heat sink, but it will profoundly affect ecosystems and their biodiversity, given the stability of this cold environment. For example, warming in South America has induced poleward range shifts in predatory crab to the Antarctic where communities have evolved without the presence of crushing predators for millions of years (Smith *et al.*, 2012). The combination of warming, acidification, and deoxygenation, described as a "triple whammy" of stressors, is predicted to reduce habitat suitability for habitat-forming calcifiers such as cold-water corals (Gruber, 2011; Lunden *et al.*, 2014). Biodiversity also plays a key functional role in the provision of most other ES (Palumbi *et al.*, 2009; Science for Environment Policy, 2015), although the exact relationship remains unclear (Balvanera *et al.*, 2014). As these impacts continue to reveal themselves, deep-sea biological communities grow increasingly vulnerable.

JURISDICTIONAL CHALLENGES OF DSES IMPLEMENTATION

There exist challenges to the operationalization of an ES approach in the deep sea. These include how functions translate into services, recovery potential and times, and the economic valuation of ES, which are related to lack of knowledge and data (Le *et al.*, in press). Other challenges, such as those regarding jurisdiction and enforcement, are borne out of gaps in a regulatory framework still in development.

The deep sea is the largest ecosystem on Earth, making up more than 90% of the liveable volume on the planet (Levin and Le Bris, 2015). However, most of it lies outside of countries' exclusive economic zones (EEZs) and must, therefore, be regulated and managed internationally. A common management tool is marine spatial planning, which could potentially utilize DSES in designating marine protected areas (MPAs). For example, an ES-value threshold could be established with baseline estimates of ES provision, and any areas that provide ES with value higher than that threshold could be given spatial protections. The international nature of many deep-sea resources makes this difficult because of overlaps and gaps in jurisdiction, and differences in management tools.

In general, MPAs exhibit higher resilience to and recovery potential after disturbance events (Huvenne *et al.*, 2016). In Areas Beyond National Jurisdiction (ABNJ), the Food and Agriculture Organization of the United Nations (FAO) has designated several deep-water species and habitats as Vulnerable Marine Ecosystems (VMEs) (*e.g.*, cold-water corals, hydrothermal vents on Reyjkanes Ridge, C-H seamounts in the Pacific). Generally, once identified, VMEs are protected from all human activities, but different management regulations may allow some fishing activity in certain protected areas (*e.g.*, MPAs).

The International Seabed Authority (ISA) has jurisdiction in ABNJ, although only on the seafloor. In addition to recognizing VMEs, the ISA can designate spatial protections called areas of particular environmental interest (APEIs) (ISA, 2011). Large sections of the Clarion-Clipperton Fracture Zone, which is a polymetallic nodule province with multiple mining exploration claims within it, have been designated as APEIs (Wedding *et al.*, 2013). Other protections in international waters include the recent "biodiversity beyond national jurisdiction" (BBNJ) instrument that the United Nations is developing (Blasiak and Yagi, 2016).

Marine Reserves (MRVs), another type of MPA where no resource extraction is allowed, are effective at increasing the abundance, diversity, and productivity of marine organisms (Lubchenco *et al.*, 2003). Furthermore, larger networks of MRVs are effective at maintaining connectivity among populations, thereby providing more protection for marine communities than a single MRV against climate change. As marine species shift their ranges from changes in temperature, oxygen, or carbonate chemistry, it is important that networks of MRVs consider novel conservation planning approaches that incorporate climate change adaptations in organisms and humans (Schmitz *et al.*, 2015; Jones *et al.*, 2016).

MPAs are important management tools because they can protect areas that provide ES and, consequently, significant value to society. Incorporating ES into spatial protections would associate a value with the MPA (i.e., the value of a MPA would be equal to the value of the ES it provides, both directly and indirectly). Estimated values of an MPA may help further inform decisions regarding enforcement (*e.g.*, how much to provide, who is responsible). Although economic valuation is currently difficult, it will become more manageable and accurate as more knowledge and data regarding DSES accrue.

THE DSES "CHARISMA" GAP

Another challenge to implementing a DSES approach to management in the face of multiple climate stressors and human activities is the lack of understanding and "charisma" about the deep sea by the general public. Humans are physically and emotionally disconnected from the deep-sea environment, even more so than other ES that are out of sight (*e.g.*, Blue Carbon). The most effective way to fill this "charisma" gap is to improve scientific understanding, stewardship, and public education. It is more important than ever to raise awareness and promote transparency, accountability, research, and conservation of DSES. For example, the Deep Ocean Stewardship Initiative (DOSI) is a group of international scientists and professionals in technology, policy, law and economics that advises on ecosystem-based management of resource use in the deep sea and potential strategies that maintain the integrity of deep-sea ecosystems within and beyond national jurisdiction (http://dosi-project.org/). Live web broadcasting from the deep sea by the NOAA Office of Ocean Exploration and Research offers anyone with an internet connection the experience to witness what biological and earth processes occur in the deep ocean. Amid other deep-sea researchers and explorers, these organizations emphasize the importance of interdisciplinary approaches to better understand how the deep ocean functions and how the services it provides will change under future climate change scenarios.

CONCLUSION

The deep sea is the largest ecosystem on Earth and hosts a diversity of habitats that provide value to society as a result of their functioning. These ecosystem services can be extractive (*e.g.*, fishing) or non-extractive (*e.g.*, climate regulation), and it is essential to consider both in environmental management especially in the face of multiple stressors related to climate and human activity. As CO_2 emissions continue to increase, deep-sea climate regulation may become increasingly important to recognize in order to continue benefitting from this service, which also influences other services related to biogeochemical cycles and biological communities (Fig. 1). Although there are still challenges to be addressed in the deep sea (*e.g.*, scientific uncertainty, jurisdictional gaps, lack of public engagement), development of protective measures against environmental degradation and emergencies now may help ensure the environmentally and economically sustainable use of the deep sea and its many ecosystem services.

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REFERENCES

- ARMSTRONG C.W., FOLEY N.S., TINCH R. and VAN DEN HOVE S., 2012 – *Services from the Deep: Steps Towards Valuation of Deep Sea Goods and Services*. Ecosyst. Serv. 2, 2–13. doi:10.1016/j.ecoser.2012.07.001.
- BALVANERA P., SIDDIQUE I., DEE L., PAQUETTE A., ISBELL F., GONZALEZ A., BYRNES J., O'CONNOR M.I., HUNGATE B.A. and GRIFFIN J.N., 2014 – *Linking Biodiversity and Ecosystem Services: Current Uncertainties and the Necessary Next Steps*. Bioscience. 64, 49-57. doi: 10.1093/biosci/bit003.
- BLASIAK R. and YAGI N., 2016 – *Shaping an International Agreement on Marine Biodiversity Beyond Areas of National Jurisdiction: Lessons From High Seas Fisheries*. Marine Policy. 71, 210-216. Doi: 10.1016/j.marpol.2016.06.004.
- BUHL-MOTENSEN L., ELLINGSEN K.E., BUHL-MORTENSEN P., SKAAR K.L. and GONZALEZ-MIRELES G., 2015 – *Trawling Disturbance on Megabenthos and Sediment in the Barents Sea: Chronic Effects On Density, Diversity, And Composition*. ICES J. Mar. Sci. doi: 10.1093/icesjms/fsv200.
- CRAIN C. M., KROEKER K. and HALPERN B.S., 2008 – *Interactive and Cumulative Effects of Multiple Human Stressors in Marine Systems*. Ecol. Lett. 11, 1304-1315.
- FAO, 2014 – *The State of World Fisheries and Aquaculture: Opportunities and challenges*. Food and Agriculture Organization of the United Nations, Rome.
- GRUBER N., 2011 – *Warming Up, Turning Sour, Losing Breath: Ocean Biogeochemistry under Global Change*. Phil. Trans. Roy. Soc. A., 369(1943), 1980-1996. doi: 10.1098/rsta.2011.0003.
- GUNDERSON L.H., COSNES B. and GARMESTANI A.S., 2016 – *Adaptive Governance of Riverine and Wetland Ecosystem Goods and Services*. J. Env. Man. DOI: 10.1016/j.jenvman.2016.05.024.
- HAINES-YOUNG R. and POTSCHIN M., 2013 – *Common International Classification of Ecosystem Services (CICES): Consultation on Version 4, August-December 2012*. EEA Framework Contract No EEA/IEA/09/003.
- HUVENNE V.A.I., BETT B.J., MASSON D.G., LE BAS T.P. and WHEELER A.J., 2016 – *Effectiveness of a Deep-Sea Cold-Water Coral Marine Protected Area, Following Eight Years Of Fisheries Closure*. Biol. Cons. 200, 60-69.
- International Seabed Authority, 2011 – *Environmental Management Plan for the Clarion-Clipperton Zone*. IBSA/17/LTC/7. Kingston, Jamaica.
- International Seabed Authority, 2015 – *Developing a Regulatory Framework for Mineral Exploitation in the Area*. International Seabed Authority, Kingston, Jamaica.
- IPCC, 2014 – *Climate Change 2014: Synthesis Report Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.), IPCC, Geneva, Switzerland, 151 pp.
- JOBSTVOGT N., HANLEY N., HYNES S., KENTER J. and WITTE U., 2014 – *Twenty Thousand Sterling under The Sea: Estimating the Value of Protecting Deep-Sea Biodiversity*. Ecol. Econ. 97, 10–19. doi:10.1016/j.ecolecon.2013.10.019.
- JONES K.R., WATSON J.E., POSSINGHAM H.P. and KLEIN C.J., 2016 – *Incorporating Climate Change into Spatial Conservation Prioritisation: A Review*. Biol. Cons., 194, 121-130.
- LE J.T., LEVIN L.A. and CARSON R.C., 2016 – *Incorporating Ecosystem Services into Environmental Management of Deep-Seabed Mining*. Deep Sea Res. II. doi : 10.1016/j.dsr2.2016.08.007.
- LEARY D.K., 2004 – *Bioprospecting and the Genetic Resources of Hydrothermal Vents on the High Seas: What is the Existing Legal Position, Where are we Heading and What are our Options?* Macquarie Journal of International and Comparative Environmental Law. 137.
- LEVIN L.A. and LE BRIS N., 2015 – *Deep Oceans under Climate Change*. Science 350: 766-768.
- LUBCHENCO J., PALUMBI S.R., GAINES S.D. and ANDELMAN S., 2003 – *Plugging a Hole in the Ocean: the Emerging Science of Marine Reserves*. Ecol. App., 13(1), S3-S7.
- LUNDEN J.J., MCNICHOLL C.G., SEARS C.R., MORRISON C.L. and CORDES E.E., 2014 – *Acute Survivorship of the Deep-Sea Coral Lophelia Pertusa from the Gulf of Mexico under Acidification, Warming, and Deoxygenation*. Front. Mar. Sci., 1, 78. doi:10.3389/fmars.2014.00078.

- MAHONE B.P., BHATT A., VULLA D., SUPURAN C.T. and MCKENNA R., 2015 – *Exploration of Anionic Inhibition of the α-Carbonic Anhydrase from Thiomicrospira Crunogena XCL-2 Gammaproteobacterium: a Potential Bio-Catalytic Agent for Industrial CO_2 Removal.* Chem. Eng. Sci. 138. 575-580. doi:10.1016/j.ces.2015.07.030.
- MERRIE A., DUNN D.C., METIAN M., BOUSTANY A.M., TAKEI Y., ELFERINK A.O., OTA Y., CHRISTENSEN V., HALPIN P.N. and ÖSTERBLOM H., 2014 – An ocean of surprises – *Trends in Human Use, Unexpected Dynamics and Governance Challenges in Areas Beyond National Jurisdiction*. Glob. Environ. Chang. 27, 19–31. doi:10.1016/j.gloenvcha.2014.04.012.
- Millennium Ecosystem Assessment, 2005 – *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington DC.
- NORSE E.A., BROOKE S., CHEUNG W.W.L., CLARK M.R., EKELAND I., FROESE R., GJERDE K.M., HAEDRICH R.L., HEPPELL S.S., MORATO T., MORGAN L.E., PAULY D., SUMAILA R. and WATSON R., 2012 – *Sustainability of Deep- Sea Fisheries*. Marine Policy. 36, 307-320.
- PALUMBI S.R., SANDIFER P.A., ALLAN J.D., BECK M.W., FAUTIN, D.G., FOGARTY M.J., HALPERN B.S., INCZE L.S., LEONG J.A., NORSE E., STACHOWICZ J.J. and WALL D.H., 2009 – *Managing for Ocean Biodiversity to Sustain Marine Ecosystem Services*. Front. Ecol. Environ. 7, 204–211. doi:10.1890/070135.
- RAMIREZ-LLODRA E., TYLER P.A., BAKER M.C., BERGSTAD O.A., CLARK M.R., ESCOBAR E., LEVIN L.A., MENOT L., ROWDEN A.A., SMITH C.R. and VAN DOVER C.L., 2011 – *Man and the Last Great Wilderness: Human Impact on the Deep Sea*. PLoS One, e22588. doi:10.1371/journal.pone.0022588.
- Rio Declaration on Environment and Development, 1992 – Principle 15.
- SCHMITZ O.J., LAWLER J.J., BEIER P., GROVES C., KNIGHT G., BOYCE JR D.A., BULLUCK J., JOHNSTON K.M., KLEIN M.L., MULLER K. and PIERCE D.J., 2015 – *Conserving Biodiversity: Practical Guidance about Climate Change Adaptation Approaches in Support of Land-Use Planning*. Nat. Areas J., 35(1), 190-203.
- Science for Environment Policy, 2015 – *Ecosystem Services and the Environmen*t. In-depth Report 11 produced for the European Commission, DG Environment for the Science Communication Unit, UWE, Bristol. Available at: http://ec.europa.eu/science-environment-policy.
- SEIDL R., SPIES T.A., PETERSON D.L., STEPHENS S.L. and HICKE J.A., 2016 – *Searching for Resilience: Addressing the Impacts of Changing Disturbance Regimes on Forest Ecosystem Services*. J. Appl. Ecol. 53, 120-129. doi: 10.1111/1365-2664.12511.
- SMITH C.R., GRANGE L.J., HONIG D.L., NAUDTS L., HUBER B., GUIDI L. and DOMACK E. 2011 – *A Large Population of King Crabs in Palmer Deep on the West Antarctic Peninsula Shelf and Potential Invasive Impacts*. Proc. Roy. Soc. B, rspb20111496. doi: 10.1098/rspb.2011.1496.
- TEEB, 2010 – *The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature. A Synthesis of the Approach*. Conclusions and Recommendations of TEEB.
- THURBER A.R., SWEETMAN A.K., NARAYANASWAMY B.E., JONES D.O.B., INGELS J. and HANSMAN R.L., 2014 – *Ecosystem Function and Services Provided by the Deep Sea*. Biogeosciences Discuss. 11, 3941-3963. doi: 10.5194/bgd-11-3941-2014.
- TURNER J.T., 2015 – *Zooplankton Fecal Pellets, Marine Snow, Phytodetritus and the Ocean's Biological Pump*. Prog. Oceanog., 130, 205-248.
- WATSON R.A. and MORATO T., 2013 – *Fishing Down the Deep: Accounting for Within-Species Changes in Depth of Fishing*. Fisheries Research. 140, 63-65.
- WEDDING L.M., FRIEDLANDER A.M., KITTINGER J.N., WATLING L., GAINES S.D., BENNETT M., HARDY S.M. and SMITH C.R., 2013 – *From Principles to Practice: a Spatial Approach to Systematic Conservation Planning in the Deep Sea*. Proc. Biol. Sci. 280, 20131684. doi: 10.1098/rspb.2013.1684.
- XIAO N., HERNDL G.J., HANSELL D.A., BENNER R., KATTNER G., WILHELM S.W., KIRCHMAN D.L., WEINBAUER M.G., LUO T., CHEN F. and AZAM F., 2010 – *Microbial Production of Recalcitrant Dissolved Organic Matter: Long-Term Carbon Storage in the Global Ocean*. Nature Reviews. 8, 593-599.

Marine Ecosystem Services in Europe

Clara Grillet,
Claire Bertin,
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The concept of ecosystem services (ES) refers to the multiple benefits humans gain from maintaining ecosystem health and functions. This notion has theoretical and practical implications because it frames scientific findings into economic terms to raise awareness of the value of functional ecosystems. It follows that environmental management that incorporates the ecosystem service approach is economically efficient and sustainable. The ES approach is particularly useful for coastal and marine ecosystems because they traditionally lack spatial planning and protective regulation. Moreover, the concept of ecosystem services emphasizes the ocean's function as a climate regulator, and its crucial role for mitigation and adaptation to climate change. Regional implementation of integrated management already exists in the European Union. The next step now is to apply the ES approach to other, threatened regions such as the Mediterranean in order to ensure ecosystem resilience and service provision.

INTRODUCTION

The term "ecosystem services" emerged in the 1970s to raise public awareness of biodiversity conservation. It is a utilitarian concept which frames ecosystem functions as goods and services for the human population. The Convention on Biological Diversity (1992) defines ecosystems as "*a dynamic complex of plant, animal, and micro-organism communities and the non-living environment, interacting as a functional unit*". Ecosystems are therefore composed of animals, plants, minerals and humans living together in a shared space. Interactions within the ecosystem can produce various important services for human societies. These services can be linked to the exploitation of natural resources (*e.g.* timber, fish), the regulation of the environment (*e.g.* water quality, pollination), and cultural services (*e.g.* recreation, natural patrimony). However, many human lifestyles create significant pressures on their ecosystems' natural capital (*i.e.* resources) and functions. As a result, human activities such as overfishing, oil drilling, waste disposal and shipping impact ecosystems' ability to provide services both directly and indirectly (Costanza *et al.*, 2014). The concept of ES has been developed to assess how man-made pressures affect ecosystem health and service provision.

The ES approach aims at evaluating these strains by integrating ecology and economics. It identifies ecological functions and translates them into economic units. As an ecosystem functions using its natural resources, it produces goods and services that increase human wellbeing (Van den Belt *et al.*, 2016). For instance, one coastal ecosystem has a set amount of natural capital in the form of mangroves. Mangroves serve as habitat for fish, especially nurseries for juveniles (Chumra *et al.*, 2003). By protecting juvenile fish, mangroves maintain and even increase the quantity of available fish in local fisheries (Aburto-Oropeza *et al.*, 2008). Hence this ecosystem provides a valuable service, *i.e.* supplying food and livelihoods. The same territory often provides additional services. Mangroves are among the most biochemically active natural systems in the world, and are consequently important carbon sinks (Chumra *et al.*, 2003; Barbier *et al.*, 2011). Moreover, mangroves' intricate root systems mitigate coastal erosion (Wolanski, 2007). Therefore the concept of ecosystem services examines how people depend on ecosystems, what benefits ecosystems provide in a utilitarian sense, and how to better manage and protect ecosystems for the benefit of both nature and people.

AN ANTHROPOCENTRIC CONCEPT

The concept of ES is essentially human-centered. Ecosystem functions are only considered to be services if they improve the life of humans. There have been several attempts to classify the different kinds of services ecosystems supply. One common typology is the Millennium Ecosystem Assessment (Millenium Ecosystem Assessment, 2005). This framework divides ES into four groups. Other categorizations such as The Economics of Ecosystems and Biodiversity (TEEB, 2010) use similar groupings. Typologies commonly find that coastal and marine ecosystems provide:

- Provisioning services: fisheries, bioprospecting, building materials;
- Supporting services: life-cycle maintenance for both fauna and flora, primary and secondary production, nutrient cycling;
- Regulating services: carbon sequestration and storage, erosion prevention, waste-water treatment, moderation of extreme events;
- Cultural services: touristic, recreational, aesthetic and spiritual benefits.

The ocean – from the coast down to the deep sea – covers the majority of the planet and provides a host of services, both extractive and non-extractive, to society. In many cases, non-extractive benefits are not considered during the decision-making process although they may be significant (*e.g.* the ocean absorbs approximately one third of emitted carbon dioxide (IPCC, 2014)). Marine ES are generally taken for granted. Fish are expected to live in the sea, boats to be navigating on it, and tourists to freely walk on the beach. Because these services are considered a given, they are rarely accounted for when making planning or investment decisions. The ES approach aims to highlight the hidden benefits humans gain from their ecosystem, for instance by giving services a monetary value (TEEB, 2010). It is difficult to value the flow of coastal and marine ecosystem services and goods because the same ecosystem can have a local, regional, or global impact, and gathering

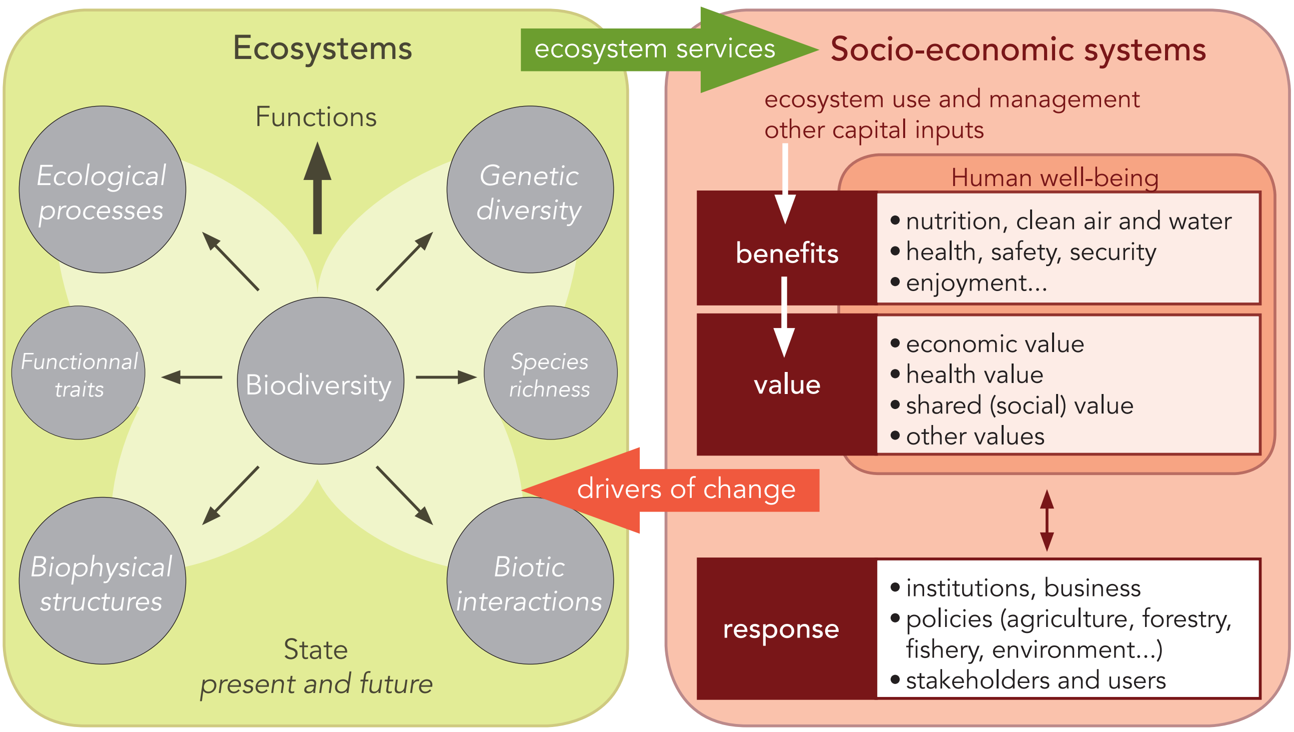

Fig.1 – Conceptual framework for EU wide ecosystem assessments. © biodiversity.europa.eu/maes.

sufficiently precise data is tedious (Pendleton, 2016). Nevertheless, extensive studies conclude that the global value of marine and coastal ecosystem services amounted to 20.9 trillion US dollars in 2011 (Costanza *et al.*, 2014). In spite of great biodiversity loss, *e.g.* the deterioration of coral reefs, ecosystem services are more greatly valued today than twenty years ago thanks to greater research in the field.

MARINE ECOSYSTEM SERVICES AND CLIMATE CHANGE

More data has shown that several ecosystem services are directly related to climate change policy, either for mitigation or adaptation. First and foremost, several coastal and marine ecosystems are important for carbon sequestration. The potential of coastal ecosystems such as mangroves seagrasses and marshes, to store and retain carbon is non-negligible. The destruction of these ecosystems is estimated to cost $USD 6-42 billion annually in economic damages (Pendleton *et al.*, 2012). Current projects are attempting to assess if these ecosystems may be covered by REDD+ (Reducing Emissions from Deforestation and Forest Degradation) mechanisms in the future (Herr *et al.*).

In terms of adaptation, coastal and marine ecosystems sustain the livelihoods of millions of people worldwide through fisheries and tourism (Allison *et al.*, 2016). Mangroves and coral reefs provide coastal protection to nearby coastal towns and cities, an increasingly important service due to sea-level rise and the change in cyclone patterns (Das and Vincent 2009; Gedan *et al.*, 2010; Pramova *et al.*, 2012). Seagrasses and oyster beds may also provide coastal protection (Swann, 2008).

It is possible that the adverse effects of climate change (*i.e.* increasing sea temperature, ocean acidification, deoxygenation, sea-level rise, extreme weather events) will modify or impair the provision of coastal and marine ecosystem goods and services in the future (Craft *et al.*, 2009). Assessing current provisions of ecosystem services from coastal and marine ecosystems is therefore important to understand future trade-offs and opportunities to tackle global issues such as climate change.

MANAGING ECOSYSTEM SERVICES IN A MARINE ENVIRONMENT

The concept of ecosystem services originated from terrestrial systems and has since been applied to the coastal and marine realm, without taking into account the marine environment's unique challenges. The ocean has more fluid boundaries relative to terrestrial systems, which makes it difficult to map the flow of services without more scientific data (Jobstvogt *et al.*, 2014). Marine spatial planning is therefore less developed and has now only emerged recently as a mainstream political issue. The ocean is also tightly linked to the atmosphere (and sometimes land), which can change its chemistry and mixing (Screen and Francis, 2016). These complex and interconnected relationships can make it difficult to effectively manage coastal and marine systems and may require innovative strategies to address.

Moreover, implementing regulation is often complicated by questions of jurisdictions. States have jurisdiction over their Exclusive Economic Zone (EEZ), which is usually limited to 200 nautical miles from the coastline or may at the maximum extend to the end of the continental shelf. This breakdown means that a considerable part of the ocean is not subject to State regulation. To effectively protect marine ecosystems, the United Nations Convention on the Law of the Sea (UNCLOS, 1982) defines the rights and responsibilities that members have to the global ocean. The agreement also established other governing bodies, such as the International Seabed Authority (ISA) which governs the international seafloor and its resources. But the question of managing areas beyond national jurisdictions such as the water column and the seabed still remains. Collaborative action among States is often the only way to create a legal framework for protecting ecosystems.

Human societies have every reason to adopt a protective and sustainable development approach to their coastal and marine ecosystems. Although the translation between ecological processes and ecosystem services is still unclear in many cases, biodiversity is often at the core of service provision (Palumbi *et al.* 2008, Cardinale *et al.*, 2012) as well as resilience and the ability to recover from impacts (Worm *et al.*, 2006; Lindegren *et al.*, 2016). Healthy ecosystems can provide greater benefits (both monetary and non-monetary) relative to disturbed or degraded ones. Integrating the concept of ecosystem services into existing management tools, such as marine spatial planning and ecosystem-based management, becomes increasingly important as the human footprint on the ocean continues to grow (Böhnke-Henrichs *et al.*, 2013). The deep sea in particular is becoming more and more affected by human activity (Le and Sato, 2016; Ramirez-Llodra *et al.*, 2011). Fishing for instance increasingly impacts deep-sea ecosystems as fisheries are moving deeper into the water column due to warming waters. Fossil fuel companies too are showing greater interest in deep-sea mineral and oil resources, as submerged deposits are gradually running out.

A USEFUL TOOL FOR SUSTAINABLE MANAGEMENT OF MARINE AND COASTAL ECOSYSTEMS

Current programs to assess marine and coastal ecosystem services are already in place internationally, at the global, national and local scales. These assessments serve three purposes: first to systematically assess the benefits in terms of goods and services that the ocean or specific ocean and coastal ecosystems provide; to gather information to improve management and marine planning, and lastly to communicate the value of the ocean. Systematic assessments, like the French national project "Évaluation Française des Écosystèmes et Services Écosystémiques", identify trade-offs and opportunities to better manage biodiversity (EFESE, 2016). Other types of ES assessments can be used to improve marine planning and management at more local scales. The VALMER project for example attempted to assess ecosystem services in the

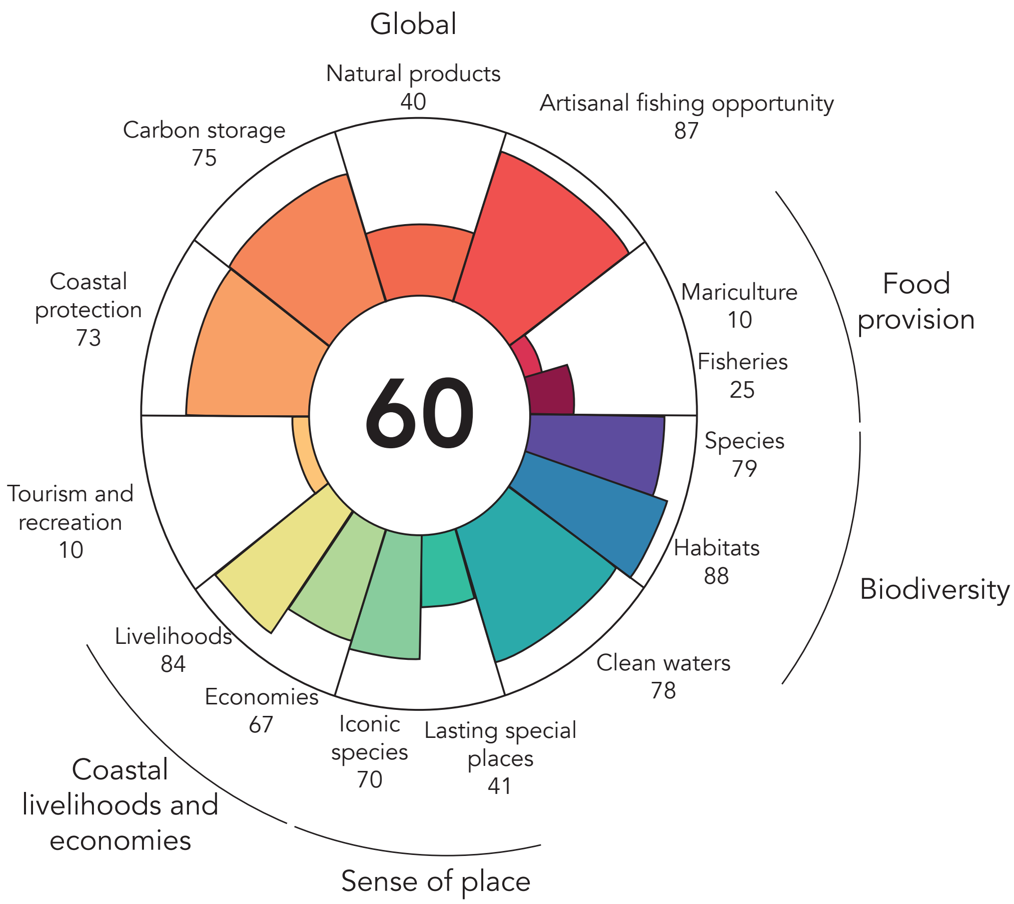

Fig.2 – Indicators of the OHI Index. © Halpern *et al.*, 2012 With permission.

English Channel to inform management and planning (VALMER, 2016). Ecosystem services assessments can also be used for communication purposes on the role of coastal and marine environments. One often cited example is the value of sharks in Palau, that is estimated at $1.9 million when alive, 16.6 times more than the value of shark fin. In addition, a recent comprehensive study by WWF (Ocean Wealth Report, 2015) aims at advertising the tremendous value of the marine environment. But these evaluations are often conducted during State-specific assessments, which makes it difficult to compare the results with foreign assessments and agree on the state of biodiversity in transnational ecosystems.

Since 2012, a new indicator has been developed to remediate this situation. The Ocean Health Index (OHI) compiles data from all over the world and assesses the health of States' sea waters within their Exclusive Economic Zone (Halpern *et al.*, 2012). The OHI rates countries based on a variety of indicators to identify key points of pressure, improvement and strength. This innovative index is a standardized and transparent measure which incorporates competing public goals (exploitative and preservationist uses of ocean resources). It is meant "*to be used by scientists, managers, policy makers and the public*" to evaluate and communicate about results of integrated management policies (Halpern *et al.*, 2012). The OHI could be particularly useful to promote collaboration between States and assess trends in marine ecosystem health globally, as well as inform decison makers at the national level.

INTEGRATING THE CONCEPT OF ECOSYSTEM SERVICES INTO POLICYMAKING AND POLICY DESIGN: THE EUROPEAN UNION'S COLLABORATIVE APPROACH

Integrated policies, which take into account the ecosystem service approach, are already being put into practice within the European Union (EU). Since June 17, 2008, all EU Member States must abide by the Marine Strategy Framework Directive (MSFD 2008/56/CE), which commits in its article 1.3 to applying an ecosystem-based approach to enable the "*sustainable use of marine goods and services*" (Europa, 2016). The directive aims at achieving Good Environmental Status (GSE) for all marine waters by 2020. GSE is assessed using 11 qualitative criteria, which evaluate an ecosystem's ability to function properly and sustainably (MEEM, 2013). The MSFD follows the ecosystem service approach thanks to integrated management: marine ecosystems are protected with the aim of safeguarding ecological functions. In France for instance, maritime zones are divided in many subregions, which reflect large ecosystems and administrative boundaries. Each subregion elaborates and implements a Marine Environment Action Plan (MEAP) (Ministère de l'Ecologie, 2011). Every stakeholder – elected officials, scientists, and fishermen among others – is invited to conciliation meetings, and public consultations are organized to analyze the situation in terms of physical, biological, economic, and social characteristics, as well as man-made pressures on the environment and policy objectives (Direction Interrégionale de la Mer, 2015). At the EU level, there are several working groups in charge of coordinating national policies to ensure that all EU waters are equally protected throughout the European Union. Moreover, the ES approach of the directive aims at making neighboring States collaborate and take action together to protect common ecosystems in an attempt to ensure that they will work properly and provide us with services.

A SUCCESSFUL EXAMPLE OF INTEGRATED MANAGEMENT IN THE MEDITERRANEAN: POSIDONIA MEADOWS

Posidonia meadows (*posidonia oceanica*) are underwater flowering plants, which grow slowly – 1 m in 100 years-on the Mediterranean coasts (Boudouresque *et al.*, 2010). They are endemic to the Mediterranean Sea and play an essential role in marine biodiversity. Up to 50 endemic species, *i.e.* species that can only grow in a certain habitat, dwell there (Campagne *et al.*, 2015). These meadows have various ecological functions: they constitute an important food source for species like urchins or wrasses; many fish come there to reproduce and to establish nurseries for their offspring, giving them a protected place to develop into adult fish. Moreover, thanks to their rhizomes and roots, posidonia meadows hold sediments on friable soil, thus effectively protecting the coastline against erosion caused by weather events, such as storms. Similarly, dead posidonia leaves help protect beaches by preventing currents and winds from taking sand away during storms. Furthermore, seagrass meadows are recreational hotspots for human activities such as snorkeling and diving, while also supporting traditional fishing, and mitigating climate change by sequestering carbon.

However, posidonia meadows are vulnerable to high human disturbance: boat anchors wrench them out, coastal urbanization, greater infrastructure – ports, levees – all destroy these habitats (Telesca *et al.*, 2015). Fewer Posidiona plants means less protection against erosion, both along the coastline and on the beach (Vassalolo *et al.*, 2013). Moreover, habitat destruction and deterioration has adverse impacts on marine species housed by the seagrass beds, which leads to biodiversity loss as species leave or disappear. This in turn results in less fish in the area, so fishermen suffer, along with recreational activities that lose their attractiveness.

CONCLUSION

The concept of ecosystem services is an anthropocentric notion, which aims at highlighting the benefits humans receive from living in fully functioning ecosystems. Economic valuation of such services becomes the yardstick for all stakeholders to collaboratively decide on the best policies to protect and sustainably use multiple ecosystems. The ecosystem service approach is particularly useful to manage coastal and marine ecosystems, which are tremendously valuable, especially with regards to climate change. The concept is needed to promote integrated management of natural resources. As ecosystems know no borders, the notion of ecosystem services is helpful for States to collaborate on protecting and using common resources sustainably in order to keep benefiting from ecosystems. Because a damaged ecosystem will produce less services, the total costs associated with non-integrated management will be higher than with using the ecosystem service approach. Therefore, taking advantage of the ecosystem service approach is ecologically and economically smart, as it substantially saves money while encouraging sustainable management and the reaping of greater coastal and marine ecosystem benefits in the long term.

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REFERENCES

- ALLISON E. H. and BASSETT H. R., 2015 – *Climate Change in the Oceans : Human Impacts and Responses*. Science, 350 (6262), 778-782.
- ABURTOOROPEZA O., EZCURRA E., DANEMANN G., VALDEZ V., MURRAY J. and SALA E., 2008 – *Mangroves in the Gulf of California Increase Fishery Yields.* In : PNAS, 105 (30) : 1045610459. doi : 10.1073/pnas.08046011050.
- BARBIER E. B., HACKER S. D., KENNEDY C., KOCH E. W., STIER A. C. and SILLIMAN B. R., 2011 – *The Value of Estuarine and Coastal Ecosystem Services in Ecological Monographs.* 81 : 169 – 193. doi : 10.1890/101510.1.
- BOHNKEHENRICHS A., BAULCOMB C., KOSS R., HUSSAIN S. S. and DE GROOT R.S., 2013 – *Typology and Indicators of Ecosystem Services for Marine Spatial Planning and Management in Journal of Environmental Management.* 130 : 135140. doi : 10.1016/j.envman.2013.08.027.
- BOUDOURESQUE C., 2010 – *Structure et fonctionnement des écosystèmes benthiques marins. L'écosystème à Posidonia oceanica.* Centre d'océanologie de Marseille. http ://www.com.univmrs.fr/~boudouresque/Documents_enseignement/Ecosystemes_MPO_3_Posidonia_web_2010.pdf.
- CAMPAGNE C., SALLES J.-M., BOISSERY P. and DATER J., 2015 – *The Seagrass Posidonia Oceanica : Ecosystem Services Identification and Economic Evaluation of Goods and Benefits in Marine Pollution Bulletin*. Volume 97, Issues 1-2, pp. 391-400.
- CARDINALE B. J., DUFFY J. E., GONZALEZ A., HOOPER D. U., PERRINGS C. *et al.*, 2012 – *Biodiversity Loss and Its Impact on Humanity.* Nature. 486 : 5967. doi : 10.1038/nature11148.
- COSTANZA R., D'ARGE R., DE GROOT R., FARBERK S., GRASSO M., HANNON B., LIMBURG K., NAEEM S., O'NEILL R., PARUELO V. L, RASKIN J., SUTTONKK R. G. and VAN DEN BELT P., 1997 – *The Value of the World's Ecosystem Services and Natural Capital.* Nature. Vol. 387 : 253260.
- COSTANZA R., DE GROOT R., SUTTON P., VAN DER PLOEG S., ANDERSON S. J., KUBISZEWSKI I., FARBER S. and KERRY TURNER R., 2014 – *Changes in the Global Value of Ecosystem Services in Global Environmental Change*. Vol. 26 : 152158.
- DIRECTION INTERREGIONALE DE LA MER NORD ATLANTIQUE MANCHE OUEST, 2015 – *Plans d'actions pour le milieu marin : consultation du public sur les programmes de mesures.* http ://www.dirm.nordatlantiquemancheouest.developpementdurable.gouv.fr/plansdactionspourlemilieumarinconsultationa418.html#sommaire_1.
- EFESE, 2016 – *L'essentiel du cadre conceptuel.* http ://www.developpementdurable.gouv.fr/IMG/pdf/Efese_cadre_conceptuel.pdf.
- EUROPA, 2016 – *European Commission, Environment, Marine and Coast, Coastal and marine policy. Our Oceans, Seas and Coasts.*
- GATTUSO J. P., MAGNAN A., BILLÉ R., CHEUNG W. W. L., HOWES E. L., JOOS F. and HOEGH-GULDBERG, O., 2015 – *Contrasting Futures for Ocean and Society from Different Anthropogenic Co_2 Emissions Scenarios*. Science, 349 (6243), aac4722.
- 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., STUART CHAPIN F., CROWDER L. B., DALY K. L., DONEY S. C., ELFES C., FOGARTY M. J., GAINES D. S., JACOBSEN K. I., BUNCE KARRER L., LESLIE H. M., NEELEY E., PAULY D., POLASKY S., RIS B., ST MARTIN K., STONE G. S., RASHID SUMAILA U. and ZELLER D., 2012 – *An Index to Assess the Health and Benefits of the Global Ocean.* Nature, 488 : 615-622. http://ec.europa.eu/environment/marine/eucoastandmarinepolicy/marinest rategyframeworkdirective/index_en.htm
- HERR D., PIDGEON E. and LAFFOLEY D. (eds.), 2011 – *Blue Carbon Policy Framework : Based on the first workshop of the International Blue Carbon Policy Working Group*. Gland, Switzerland : IUCN and Arlington, USA : CI. vi + 39pp.
- IFREMER – *Directive Cadre Stratégie Pour le Milieu Marin, Niveau national.* http://sextant.ifremer.fr/fr/web/dcsmm/niveaunational.
- IPCC, 2014 – *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.).

IPCC, Geneva, Switzerland, 151 pp.
- JOBSTVOGT N., TOWNSEND M., WITTE U. and HANLEY N., 2014 – *How Can We Identify and Communicate the Ecological Value of Deepsea Ecosystem Services?* PLoS ONE. 9 (7): e1000646. doi: 10.11371/journal.pone.01000646.
- JOLLY D., 2011 – *Priced Off the Menu? Palau's Sharks Are Worth $1.7 Million Each, a Study Says*. The New York Times, 2 May 2011.
- LE J. T. and SATO K. N., 2016 – *Ecosystem Services of the Deep Ocean.* Ocean and Climate Platform, www.ocean-climate.org.
- LINDEGREN M., CHECKLEY D. M., OHMAN M. D., KOSLOZ J. A. and GOERICKE R., 2016 – *Resilience and Stability of a Pelagic Marine Ecosystem*. Proc. R. Soc. B. doi: 10.1098/rspb.2015.1931.
- MILLENIUM ECOSYSTEM ASSESSMENT, 2005 – *Ecosystems and Human Wellbeing: a Framework for Assessment*. Island Press, 2005: 2536 at http://millenniumassessment.org/documents/document.765.aspx.pdf.
- MINISTERE DE L'ECOLOGIE, DU DEVELOPPEMENT DURABLE, DES TRANSPORTS ET DU LOGEMENT, 2011 – *Pour un bon état écologique du milieu marin. La mise en œuvre de la directive-cadre stratégie pour le milieu marin.* http://www.dirmmemn.developpementdurable.gouv.fr/IMG/pdf/2011_06_06_brochure_DCSMM.pdf.
- MINISTÈRE DE L'ENVIRONNEMENT, DE L'ÉNERGIE ET DE LA MER, 2013 – *Pour un bon état écologique du milieu marin en 2020. La mise en œuvre de la directive-cadre stratégie pour le milieu marin*.
- PALUMBI S. R., SANDIFER P. A., ALLAN J. D., BECK M. W. and FAUTIN D. G. *et al.*, 2008 – *Managing for Ocean Biodiversity to Sustain Marine Ecosystem Services.* Front. Ecol. Environ. 7 (9): 204211. doi: 10.1890/070135.
- PENDLETON L., DONATO D. C., MURRAY B. C., CROOKS S., JENKINS W. A., SIFLEET S. and MEGONIGAL P., 2012 – *Estimating Global "Blue Carbon" Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems.* PloS one, 7 (9), e43542.
- PENDLETON L. H., THEBAUD O., MONGRUEL R. C. and LEVREL H., 2016 – *Has the value of global marine and coastal ecosystem services changed?* Marine Policy 64 (2016) 156 – 158.
- RAMIREZ-LLODRA E., TYLER P.A., BAKER M.C., BERGSTAD O.A., CLARK M.R. *et al.*, 2011 – *Man and the Last Great Wilderness: Human Impact on the Deep Sea*. PLoS ONE 6 (8): e22588. doi: 10.1371/journal.pone.0022588.
- SCREEN J. A. and FRANCIS J. A., 2006 – *Contribution of Seaice Loss to Arctic Amplification Is Regulated by Pacific Ocean Decadal Variability.* Nature Climate Change. doi: 10.1038/nclimate3011.
- THE ECONOMICS OF ECOSYSTEMS BIODIVERSITY, 2010 – *The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A Synthesis of the Approach, Conclusions and Recommendations of TEEB*. p.1-36.
- TRUEMAN C. N., JOHNSTON G., O'HEA B. and MACKENZIE K. M., 2014 – *Trophic Interactions of Fish Communities at Midwater Depths Enhance Long-Term Carbon Storage and Benthic Production on Continental Slopes.* Proceedings of the Royal Society B: Biological Sciences 281, 20140669 – 20140669.
- UNEP and GRID-ARENDAL, 2008 – *Vital Water Graphics, an Overview of the State of the World's Fresh and Marine Waters*. 2nd Edition, www.unep.org/dewa/vitalwater/article168.html.
- UNITED NATIONS, 1992 – *Convention on Biological Diversity.* www.cbd.int/doc/legal/cbden.pdf.
- VALMER, 2016 – http://www.valmer.eu.
- VAN DEN BELT M., GRANEK E., GAILL F., HALPERN B., THORNDYKE M. and BERNAL P., 2016 – *World Ocean Assessment I: The First Global Integrated Marine Assessment, Part III: Assessment of Major Ecosystem Services from the Marine Environment (Other than Provisionong Services) Chapter 3. Scientific Understanding of Ecosystem Services in World Ocean Assessment,* www.un.org/depts/los/global_reporting/WOA_RPROC/Chapter_03.pdf.
- VASSALLO P., PAOLI C., ROVERE A., MONTEFALCONE M., MORRI C. and BIANCHI C., 2013 – *The Value of the Seagrass Posidonia Oceanica: a Natural Capital Assessment*. Volume 75, Issues 1-2, 15 October 2013, pp. 157-167.
- WOLANSKI E., 2007 – *Estuarine ecohydrology.* Elsevier Science, 1st edition.
- WORM B., BARBIER E. B., BEAUMONT N., DUFFY J. E., FOLKE C. *et al.*, 2006 – *Impacts of Biodiversity Loss on Ocean Ecosystem Services.* Science. 314: 787790. doi: 10.1126/science.1132294.

Marine Protected Areas Networks and Climate Change: a Political Advocacy

Christophe Lefebvre

A healthy ocean will allow better ecosystems resilience to climate change, and consequently a reinforcement of ecosystem services crucial to the planet's viability. In light of growing pressure on the ocean, which has to include the development of new human activities, political issues must combine CO_2 emissions reduction with biodiversity conservation issues. Out of 10,000 Marine Protected Areas worldwide, many only exist on paper. Twenty maritime countries cover 80% of the surface of all Marine Protected Areas. Governance and joint management between public stakeholders, professionals and sea users are major obstacles for MPA networks operations. In order to ensure a viable climate for humanity, international and governmental policies should acquire an adaptation and mitigation logic, and include the ocean as a nature-based solution against climate change.

Knowledge on the functioning of marine ecosystems has greatly improved in the last years, in particular regarding the knowledge of systemic interrelationships with climate. This increase in marine ecosystem knowledge has allowed a raise in awareness among policymakers and accelerated their decision-making regarding ocean conservation because of the urgency of the climate situation and in view of the ocean's role as a climate regulator. Decisions taken during the United Nations Framework Convention on Climate Change COP21 and the Paris Agreement have led the way for others. The political development toward a better consideration of ocean conservation in climate policy must continue and be carried out via this knowledge improvement.

Conservation of marine ecosystems may reduce the effects of climate change; consequently the ocean is part of the nature-based solutions to climate change. Healthy marine habitats also allow marine species to adapt better to climate change.

Based on the scientific evidence that ecosystem services must be functioning properly in order to benefit the viability of the planet, including in terms of climate, governments must adopt new climate policies built on nature-based solutions. They must link these policies to the CO_2 emissions reduction policy and merge the biodiversity conservation issue with the climate issue. Marine biodiversity conservation is part of this strategy because of Marine Protected Areas.

Marine habitat conservation policies have become especially vital as blue growth increases anthropogenic impacts on the ocean. The impacts due to new maritime activities add to the increase in impacts on the sea caused by land-based human activities. These deterioration factors gradually damage marine ecosystems. Consequently, the acceleration of marine ecosystem deterioration reduces the ocean's ability to reduce climate change. It also jeopardizes coastal populations' physical, food and economic safety, in particular for Small Island Developing States.

An ambitious national strategy implies the establishment of a national body dedicated to the good management of maritime activities, capable of restoring deteriorated marine environment, and acting for the remediation of the sea. This body is essential to create, manage efficiently and lead a consistent and resilient national network of Marine Protected Areas and cooperate with countries sharing common regional seas.

In order to be efficient in relation to a joint biodiversity and climate policy, the Marine Protected Areas' policy must prioritize a strict protection of key areas for biodiversity and ecosystem services. It must aim at absolute conservation of vulnerable marine habitats of high ecological and biological value with high carbon sequestration capacity associated biomass, including coral reefs, mangroves, seagrass beds, salt marshes and estuaries. This conservation must be extended to the High Seas' deep waters, canyons and seamounts as part of the policy to be implemented within the Regional Seas Conventions. Conservation is not limited to Exclusive Economic Zones. Ecologically and Biologically Significant Marine Areas (EBSAs) prove that ecosystems overlap between waters under national jurisdiction and the High Seas. Finally, the role of Marine Protected Areas is to ensure biological and ecological connectivity which reinforces marine ecosystems' resilience. Therefore, they must be representative and consistently distributed to contribute to climate change resilience.

The concept of establishment of a global resilient network of Marine Protected Areas requires a wide range of conservation tools which fall under various sector-wide approaches. From the smallest community marine area for local fishery or ecotourism purposes (LMMA – Locally-Managed Marine Area) to great marine protected areas (LMA – Large Marine Areas), it is necessary to cross-reference and connect objectives which fall under all the ocean conservation sectorial tools. Particularly, Sensitive Sea Areas acknowledged and designated by the International Maritime Organization (IMO PSSAs) or the FAO Vulnerable Marine Areas (VME) are also part of building a global resilient network of Marine Protected Areas for climate. This integration could give consistency to the global network of Marine Protected Areas in relation to climate change. This could also facilitate ocean governance. This cross-sector approach of ocean conservation for climate can be facilitated with regional policy practices. The protocols of contracting parties to the Regional Seas Conventions must adjust their biodiversity and ecosystems conservation goals to those against climate change. In this matter, regional fisheries organisations must collaborate with the Regional Seas Conventions to develop common strategies, for instance the OSPAR Convention, which enabled the designation and the proposal of marine protected areas in high seas of the North East Atlantic. New alliances should be established in particular, to build cross-sector collaborations in the field of research on the functioning of marine ecosystems.

The solution to climate change of establishing networks of Marine Protected Areas will be improved if the cumulative effects of stress factors are reduced. The networks of Marine Protected Areas will respond better to climate change and other stress factors if they are effectively handled. Management must be adaptive yet reinforced by regulations. Administrators must also have access to logistical and technical means to complete their mission including scientific monitoring of climate impacts.

Unfortunately, the majority of countries are far from meeting these requirements. The current global network of Marine Protected Areas covers only 4% of oceans. This situation does not tally with the States' commitments agreed upon at the 2010 Nagoya 10th Conference of the Convention on Biological Diversity which set a 10% goal by 2020. Especially as scientists and NGOs, gathered in Sydney in 2014 for the World Parks Congress, advised the strict conservation of 30% of marine habitats in their full diversity and distribution.

There is a qualitative problem, in addition to this rather incomplete quantitative assessment. Most Marine Protected Areas do not have sufficient material and human resources to implement actual management and conservation measures; that is research and scientific follow-up, activity regulations, pollution reduction, monitoring, hosting and informing the general public. Out of the 10,000 worldwide Marine Protected Areas, seldom have a high protection status where samplings are prohibited. A large number of Marine Protected Areas around the world are Marine Protected Areas on paper only. In addition to this disqualifying situation to acquire legitimacy, there is spatial disparity. Twenty maritime countries cover

80% of the entire Marine Protected Areas surface in the ocean. These areas are geographically and spatially concentrated. In fact, there is competition for the title of largest Marine Protected Area in the Pacific Ocean, where anthropogenic stress is minor. It represents figures for statistics but doesn't address the issue of the creation of a large consistent network of Marine Protected Areas at a global level, which is representative and resilient and which involves over 150 maritime countries worldwide.

Government policies for the conservation of marine habitats must deal with the difficulties linked to the establishment of Marine Protected Areas, including governance and joint management of Marine Protected Areas between public stakeholders, professional sectors and ocean users. Experiences and feedback have proven that the most efficient Marine Protected Areas are those which include social-economic actors, in particular fisheries, in the process of defining ocean conservation regulations and measures. New participatory governance mechanisms must be implemented and need to embrace climate issues. This is all the more crucial as the concept of ocean conservation differs largely from the notions selected for the conservation of terrestrial habitats. Sea management based on ecosystems is an operational scientific approach which acknowledges the complexity of marine ecosystems and the existence of interconnections between their physical and biological elements to connect with very scattered and heterogeneous human activities at sea.

The use of climate issues to reinforce Marine Protected Areas establishment and management policies could enable the consideration of connections between the major elements of ecosystems and maritime social-economics, to outline marine activity spatial planning on a cross-disciplinary basis. A social-ecological approach based on knowledge, consultation and collaboration of stakeholders, policymakers and stakeholders' awareness, leads to adaptive management. Adaptive management addresses a repetitive process which consists of assessing the efficiency of management and including new scientific knowledge to adjust and apply management regimes. This process could continue to promote the achievement of ocean conservation goals, as well as those of climate in the context of blue growth.

Marine habitats conservation governmental policies have to organize virtuous circles based on maritime social-ecology and on the ecosystem approach to sea management. The spatial planning measures and ecosystem-based management will join these circles to address the adaptation to climate change issues. The political answer to ocean conservation for climate relies on the organisation of ocean governance systems, allowing a fair balance in marine spatial planning, which takes into consideration the concerns of ocean stakeholders and those of a viable climate for humanity. This marine spatial planning must be, in this regard, the converging point of "bottom up – top down" joint approaches of ocean conservation.

States with significant marine heritage and integrated maritime policies must lead the way. They must act as an incentive for other States to take governmental measures for integrated coastal management and ocean conservation. This also requires that all maritime States adopt national marine environment policies based on solid legislative and regulatory clauses and on governance and integrated management tools based on marine ecosystem conservation.

Governments must reconsider global, regional and national marine habitat conservation strategies by cross-referencing marine biodiversity issues with those of climate change and they must also address those of the ocean sustainable development goals (SDG14). International and governmental marine habitat conservation policies must join this logic of adaptation and mitigation of climate change impacts policies. United Nations environmental programs and policies must develop in this direction. The Convention on Climate Change and the Convention on Biological Diversity have gone separate ways for too long now. The consideration of a systemic relationship between marine ecosystems and climate could most certainly allow these two United Nations Conventions to converge towards a joint approach of their goals.

Ocean, Environment, Climate Change and Human Migration

Christine Causse,
Daria Mokhnacheva
and Guigone Camus

The ocean's role in climate regulation is at the heart of climate change economic and social issues, especially those related to environmental migrations. Although the ocean curbs global warming, it is considerably affected by the major disruption that is climate change. Both its regulation role and the ecosystem services it provides are threatened. Sea-level rise and the increasing frequency of destructive climate phenomena, such as cyclones or spring tides, impact human communities and as a result may trigger migration movements. Anticipating these climate phenomena could reduce the vulnerability of natural environments and the communities relying upon them.

The ocean is crucial to natural equilibriums which enable life on our planet. The importance of the ocean in climate regulation places it at the heart of climate change economic and social issues, and namely environmental migration-related issues. Whilst the ocean limits global warming, it is also affected by the latter. It changes when it is hotter, more acidic and less oxygenated. The ocean's regulation role and the ecosystem services it provides are threatened. The planet and populations' capacity to absorb climate impacts and their modes of adaptation to disequilibrium are affected.

The modifications it endures also contribute to sea-level rise and the increase in frequency of destructive climate phenomena such as huge cyclonic storms or spring tides. These major modifications of the marine environment have consequences on safety and vulnerability of human communities (floods, coastal erosion) but also economic consequences and can cause migrations.

A KEY ROLE IN CLIMATE REGULATION

The ocean constantly exchanges gas, water and heat with the atmosphere and redistributes them around the globe. These mechanisms are decisive for global climate. The ocean is also a regulator that limits global warming. In fact, the sea absorbs over 90 % of excess heat generated by the greenhouse effect. The ocean also absorbs a quarter of CO_2 emissions generated by human activity. The global ocean controls climate fluctuations which would be much more abrupt it they were only regulated by the atmosphere.

However the ocean's storage capacity is not indefinite and its ability to absorb tends to decrease in certain oceanic regions. The "carbon pump" mechanisms provided by oceans are biological and physical. If the distribution of marine biodiversity, including phytoplankton, or if physical parameters (temperature, salinity, pH) endure abrupt variations, this regulation role may be affected. The global ocean is experiencing consequences of this warming, even though impacts vary from one region to another. Scientific observations show that waters are becoming warmer, more acidic and less oxygenated. Not only does this affect the ocean's ability to keep its regulation role and resilience to face climate disruptions but this also has direct and immediate consequences on coasts and marine ecosystems.

A healthy ocean is a protected climate: State representatives gathered in Paris for COP21 in 2015 have agreed upon this statement.

A CHANGING OCEAN: CLIMATE CHANGE IMPACTS ON HUMAN COMMUNITIES

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

Sea-level rise

According to the 2014 IPCC Report, the global mean sea-level rose by nearly 20 cm in the 1901-2010 period. It is likely that extreme levels (during storms for instance) have risen since 1970. The most recent modeling reports a nearly 2 meters sea-level rise by the end of the century. If this increase is not identical in all regions, its pace may accelerate in the years to come.

This rise of the mean sea-level causes coastal erosion, which results in loss of arable land and water reserves due to salinized soil and groundwater. Coastlines have been receding and floods intensifying during spring tides or severe storms – these extreme weather events tend to increase.

Coastal facilities (housing, infrastructures, industries…) are particularly vulnerable to these weather phenomena which can cause important loss of human lives and considerable economic loss. Yet, the majority of world metropolises are located on the coast – including in South Asia and South East Asia. Lower coastal areas, such as delta great plains, are particularly attractive and the most populated areas in the world because of the resources they provide and their access to the sea. Consequently, according to the OECD, 40 million people living in major cities are threatened by submersion; this figure can only increase with the growing world population and urbanization.

Small Island States are also on the frontline against global warming. Erosion, salinization and loss of land are already a reality for those nations with limited habitable and cultivable surface area.

The overpopulated Island of Male, capital of the Maldives, is protected by dikes. Two raised artificial islands were built 2 km away by filling the lagoon with tons of sand and dead coral. They accommodate buildings, a hospital, a mosque and an airport.

Affected Marine Biodiversity: what are the impacts on livelihood?

Warming, acidification and deoxygenation of global waters also affect marine species and disrupt the ocean food web.

If some species adapt, others migrate to cooler deeper waters or to the North, or even disappear. Displacements of marine fauna have an impact on fisheries and aquaculture. Acidification affects phytoplankton with calcium based skeletons, fish larva growth, some mollusks' shell-building process or even the development of coral reefs which provide shelter to millions of marine species.

Deoxygenation (warmer waters contain less oxygen and increasing stratification due to warming surface waters which reduces ventilation) affects both coastal areas and the high seas. It could also have a major impact on shellfish farming, aquaculture and fisheries.

In addition, marine ecosystems, already threatened by pollution and a non-sustainable management of resources and human activities, are overexploited, which accelerates their degradation.

Economic activity such as fishery or tourism experience productivity loss in many regions. The Least Developed Countries (LDC) are generally the most impacted: their coastal infrastructures are more fragile (many are located in areas affected by tropical storms), and populations' subsistence is usually highly linked to fishery. For some countries such as the Small Island Developing States (SIDS), the entire economy is threatened. Other countries face increasing coastal populations migrating inland to find more safety and alternative livelihoods. Traditional communities may be confronted to radical change to adapt to major disruption in their living conditions. This phenomenon can cause a loss of cultural and identity landmarks, a feeling of insecurity, and erosion of traditions and indigenous knowledge. For some communities, migration is the only solution to climate change.

Displacement of vulnerable populations

Since 1990, The IPCC had noticed that climate change could increase population displacements, in particular in developing countries and the poorest communities, and especially in coastal areas and low islands. In fact, migrations and displacements linked to the impacts of climate change on the ocean and on the degradation of marine ecosystems are already a reality in many regions throughout the world.

Forced displacements due to floods or coastal erosion have already happened in many countries. Some

COP21 and the Paris Agreement

On December 12th, 2015, a historical agreement to combat climate change was adopted in Paris by 195 countries. For the first time since 1992, the ocean is mentioned in an additional text of the Climate Convention. This reference in the final text preamble ("*Noting the importance of ensuring the integrity of all ecosystems, including oceans…*"), shows global acknowledgement and awareness regarding the importance of the links between Ocean and Climate. In order to reinforce the consideration of the ocean's role, the Intergovernmental Panel on Climate Change decided in April 2015 to produce a Special Report dedicated to interactions between Climate, Ocean and the Cryosphere.

The Paris Agreement shows major progress regarding the acknowledgement of connections between human migration and climate change by referring to migrants in the final draft preamble[1], for the first time, and by requesting the establishment of a special task force to "*develop recommendations for integrated approaches to avert, minimize and address displacement related to the adverse impacts of climate change*"[2].

1 UNFCCC Decision 1/CP.21, preamble p.2: "Acknowledging that climate change is a common concern of humankind, Parties should, when taking action to address climate change, respect, promote and consider their respective obligations on human rights […] (and) migrants […]"
2 UNFCCC Decision 1/CP.21, Loss and Damage – articles 49 and 50, p. 7

governments, (for instance in Vietnam, Vanuatu and Papua-New Guinea) have implemented relocation strategies for vulnerable populations.

Migration can also be a collective strategy for communities whose livelihood mainly depends on threatened marine resources. For instance, in Senegal, the loss of halieutic productivity forces coastal populations to migrate to cities to find new sources of income.

Migration and forced displacements due to climate change impacts on the ocean and on the deterioration of marine ecosystems are already a reality in many regions of the world.

The IPCC 5th Assessment Report (2015) highlighted that populations with insufficient means to plan their migration are more exposed to extreme weather events, in particular in low incomes developing countries. In this context, it is important to insist on the fact that migration is a strategy of reinvention and regeneration of ways of life and livelihood.

POTENTIAL SOLUTIONS TO ADAPT

However, some marine ecosystem deteriorations and population forced displacements scenarios can be anticipated. A more sustainable management of natural marine resources, implementation of ecosystem protection and restoration projects, disaster mitigation initiatives, adaptation policy for climate change, creation of alternative jobs, or even planned and facilitated migration, could be propositions dedicated to reducing the vulnerability of natural habitats and communities which depend upon them.

Sustainable management of ecosystem services and resources

The importance of marine ecosystems for human populations is measured in terms of services and resources. They are crucial for mitigation policy (actions to reduce greenhouse effect) as they absorb CO_2 and for adaptation to climate change policy. Conservation, restoration and sustainable management of these ecosystems, including relying on indigenous know-how, can contribute to protecting the communities who depend upon them, reinforce their livelihood and prevent forced migrations.

Conservation, restoration and ecosystem services

For instance, seagrass beds, coastal wetlands, mangroves and coral reefs act as carbon sinks. They also play a role in coastal conservation by forming a buffer zone with the sea: they absorb approximately 75 to 90% of waves and swell and reduce considerably their erosion power. Finally, these ecosystems are a source of food and materials, and generate economic activity. In December 2015, during COP21, Secretary General for the Indian Ocean Commission (IOC), Jean Claude de l'Estrac, co-signed with the European Union a joint declaration acknowledging "*the importance of threats and challenges created by climate change, in particular the sea-level rise, natural risks increase, loss of biodiversity and their economic and financial impacts*" (source: IOC press review provided by IOC library). Conservation, sustainable management and restoration of these ecosystems participate in combating climate dangers and poverty.

The development of Marine Protected Areas could allow biodiversity conservation while preserving traditional livelihood activities by relying on local populations' know-how and types of governance. Many restoration projects have been initiated, including those by Small Island Developing States and along coastlines and particularly fragile estuaries around the world. Reef rehabilitation by developing artificial reefs (coral transplantation onto a structure), mangrove restoration and wetlands conservation have an immediate impact. In fact, these actions participate in the protection of land and populations by providing resources to coastal communities, which improve their livelihood. For instance, a program for the replanting of mangrove trees in American Samoa – funded by UNDP (United Nations Development Program) - has enabled the development of commercialization channels of mangrove and generated goods such as crabs, mangrove tree bark tannin extraction for dye used for the production of sarongs and arts and crafts.

In 2010, UNDP launched in Bangladesh an important program to plant mangrove trees along the coastline, in partnership with national authorities and local communities. In 2012, over 6000 ha of mangrove trees were replanted. In the Maldives, reef rehabilitation projects – consisting in coral transplantation onto an artificial structure – are paired with the development of ecotourism infrastructures.

Support vulnerable populations

Evidently, when facing a risk of extreme events, risk management policies and programs must be reinforced. They should consider more the needs of the most vulnerable populations, in order to better plan and manage "forced" population displacements (displacements following floods or extreme storms for instance).

Preparing populations to coastal risks by developing training program and awareness campaigns appears to be a priority to help these populations to better address these disasters, better adapt to climate change and better manage resources (water, food, etc.).

Also these migrations caused by flood risks or soil and freshwater salinization can be anticipated and guided by planning relocation zones. Other solutions should be considered to anticipate a lack of space.

In order to reduce the vulnerability of communities exposed to risks, related to sudden disasters or slow deteriorations (soil and freshwater salinization for example), a population relocation can be considered as a solution if it is anticipated and conducted by policy and long term plans. These plans should take into consideration specific needs of affected populations. They can designate rehousing areas, or consider other solutions when the surface area is limited. For example, in the Maldives, artificial islands have been built by filling the lagoon to set up an airport, a hospital, housing and schools. Due to partial submersion and salinization, the Republic of Kiribati has already purchased some land in Fiji (28 km^2) to grow food crops and provide for part of the population in case of poor soil fertility and extreme risks.

Other countries such as Tuvalu, Papua-New Guinea, Tonga and the Cook Islands are considering, in the more or less long term, relocating their communities. These countries now include in their national adaptation to climate change plan, planned migration and relocation.

Some States are starting to acknowledge the benefits of migration and migrants' potential in disaster risk management and adaptation, including through the transfer of competencies or targeted fund transfers. By removing transfer fees or even by creating special funds, Samoa and Indonesia have facilitated fund transfers from their diaspora. Some of these financial aids are intended to help rebuild after natural disasters. Other countries innovate in investment mechanisms in order to attract their diaspora's capital towards adaptation to climate change projects (for instance projects which could include marine ecosystems restoration or the development of sustainable fisheries techniques).

Others, including SIDS, develop bilateral or regional migration agreements, which could allow populations, affected by damaging consequences of climate change, to diversify their resources by working abroad.

Collaborate to move forward

In April 2016, for the signature of the Climate Agreement at the United Nations, many heads of States and heads of Governments shared their hopes and expectations. Mr. Ahmed Ali Silay, Minister Delegate in charge of International Cooperation of Djibouti declared: "*Desertification, soil depletion, droughts, wells drying up, floods and sea-level rise are recurring risks that our populations are combating as best as they can with their limited resources. Also, we must place mitigation and adaptation to climate change at the center of our actions to combat poverty in all of our countries.*" Representatives from many developing countries also highlighted the fact that their greenhouse gas emissions are very low but their populations are nevertheless the most exposed to climate disasters. Consequently, they are unanimously calling for international solidarity. In fact, international mobilization, establishment of partnership and cooperation for development policies, technology transfers, releasing international funding to develop mitigation and adaptation policies are essential to limit climate change impacts and population displacements.

As for the Ocean, on June 8th 2016 during the World Ocean's Day, UN Secretary General, Mr. Ban Ki-moon, stated that ocean health is a priority for implementation measures of the Paris Agreement, to mitigate and adapt to climate change.

The growing acknowledgment of links between Ocean, Climate and Human migrations has impelled the International Organization for Migration (IOM) and the Ocean & Climate Platform to unite in order to improve comprehension and awareness of the interactions between these three fields.

The International Organization for Migration (IOM) is an intergovernmental organization with 165 Member States. Established in 1951, IOM is the leading intergovernmental organization in the field of migration. IOM works to help ensure the orderly and humane management of migration, to promote international cooperation on migration issues, to assist in the search for practical solutions to migration problems and to provide humanitarian assistance to migrants in need, including refugees and internally displaced people. For over 20 years, IOM has been exploring the links between migration, environment and climate change through research, political relations and fieldwork.

REFERENCES

- Australian Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organisation (CSIRO), 2014 – *Climate Variability, Extremes and Change in the Western Tropical Pacific: New Science and Updated Country Reports*.
- BELL J.D. *et al.*, 2011 – *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*. Secretariat of the Pacific Community, Noumea, New Caledonia.
- COURNIL C. and GEMENNE F., 2010 – *Les populations insulaires face au changement climatique : des migrations à anticiper*. Vertigo. Revue électronique en sciences de l'environnement, 10 (3).
- DASGUPTA S., LAPLANTE B., MEISNER C., WHEELER D. and YAN J., 2007 – *The Impact of Sea Level Rise on Developing Countries: a Comparative Analysis*. Climatic Change, 93 (3), p. 379–388.
- Foresight, 2011 – *Migration and Global Environmental Change*. Final Project Report, Londres, Government Office for Science.
- IOM, 2014 – *IOM Outlook on Migration, Environment and Climate Change*. Genève, International Organization for Migration.
- IONESCO D., MOKHNACHEVA D. and GEMENNE F., 2016 – *Atlas des migrations environnementales*. Paris, Presses de Sciences Po.
- IPCC, 2014 – *Climate Change 2014: Impacts, Adaptation, and Vulnerability.* Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, sous la direction de C.B. FIELD, V.R. BARROS, D.J. DOKKEN, K.J. MACH, M.D. MASTRANDREA, T.E. BILIR, M. CHATTERJEE, K.L. EBI, Y.O. ESTRADA, R.C. GENOVA, B. GIRMA, E.S. KISSEL, A.N. LEVY, S. MACCRACKEN, P.R. MASTRANDREA and L.L. WHITE, Cambridge, Cambridge University Press.
- MATHIS J.T., COOLEY S.R., LUCEY N., COLT S., EKSTROM J., HURST T., HAURI C., EVANS W., CROSS J.N. and FEELY R. A., 2015 – *Ocean Acidification Risk Assessment for Alaska's Fishery Sector.* Progress in Oceanography, 136, p. 71–91.
- NICHOLLS R.J., HANSON S., HERWEIJER C., PATMORE N., HALLEGATTE S., CORFEE-MORLOT J., CHÂTEAU J. and MUIR-WOOD R., 2008 – *Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes: Exposure Estimates*. OECD Environment Working Paper, 1, Paris, OECD Publishing.
- OCEAN AND CLIMATE, 2015 – *Scientific Notes*. www.ocean-climate.org, 116 pages, October 2015.
- PIGUET E. and LACZKO F., 2014 – *People on the Move in a Changing Climate: The Regional Impact of Environmental Change on Migration*. Dordrecht, Springer.
- UNFCCC – *United Nations Framework Convention on Climate change*, http://unfccc.int/ [visited 04/07/2016].
- United Nations – *Meetings coverage and press releases*, [online], www.un.org/press/fr/2016/envdev1659.doc.htm [visited 18/07/2016].

Louise Ras

The Ocean in National Contributions of Mediterranean States

COP21 marked the enshrinement of national contributions in international climate negotiations. The ocean, presented at COP21 as "*the forgotten element*"[1] of international climate negotiations, has been put back on the negotiation table. As for all subjects, the ocean had to be fervently defended to access the international political agenda. What are intended nationally determined contributions and how do States prepare them? Today, how is the ocean taken into account by Mediterranean States in their national contributions?

The Mediterranean Sea, cradle of humanity, has been subjected to many anthropic modifications – namely on the coastline. The semi-closed sea is often described as an ideal study-zone, a form of miniature ocean. This region is just as interesting on the political and economic level, as it is composed of strongly diverging States. The Mediterranean thus appears fitting to study how the ocean is taken into account in Intended Nationally Determined Contributions (INDC), and to seek a better understanding of what pushes – or dissuades – a State to integrate the ocean in their adaptation and mitigation policies.

After a brief historical overview on the development of national contributions, we will look more in depth at how States form their interests in the field of environmental protection in order to better understand why the Mediterranean States are more or less interested in the ocean in said contributions.

NATIONAL CONTRIBUTIONS

For many years, the dominating approach in climate negotiations was to launch a policy at the international level to push action on the national level (top down). For instance, the majority of ministries of environment were created after the United Nations Environment Programme (UNEP), in 1972, which encouraged such a measure. The 19th session of the Conference of Parties at the United Nations Framework Convention on Climate Change (UNFCCC, Warsaw, November 2013) adopted an opposite logic (bottom-up) by proposing a system of nationally determined contributions. These are "*public outlines of what individual countries plan to do to deal with a changing climate, starting in 2020 under a new international climate agreement.*"[2] The States first agree on their objectives in relation to the UNFCCC. Goals are detailed in a treaty, the Paris Agreement, adopted at COP21 in December 2015 in Paris. Although they are not legally binding, INDCs communicate these goals "*in a manner that facilitates the clarity, transparency and understanding of the intended contributions*"[3].

These contributions combine ambitious and fair commitments in terms of both adaptation and mitigation with national priorities that are specific to each country. Year

1 Policy recommendations of the Ocean and Climate Platform.

2 "Decoding Intended Nationally Determined Contributions (INDCS): A Guide for Understanding Country Commitments", World Resources Institute, July 2015.

3 See article 2.b of the decision "Further advancing the Durban Platform" (1/CP.19).

of reference, deadline of the political agenda setting, scope, methodology used, as well as an estimation of the fairness and the ambition of the contribution in relation to national circumstances all appear in the contribution.

No formal obligation is required of INDCs. Some are rather short, limited to quantified commitments, whereas others can reach up to twenty pages and detail the country's ambitions sector by sector. The European Union's contribution is only five pages, overviewing its fairness and ambitiousness, and then making an inventory of the economic sectors it concerns. This contribution is centred on a quantified reduction of emissions. To the contrary, the Moroccan contribution – 17 pages – details at length the country's national circumstances, namely strong economic and demographic growth in context of climate change. The Moroccan INDC proposes a first unconditional and objective reduction of emission reduction, and a second objective, depending on international aid received. It then develops policies both in terms of mitigation and adaptation.

A bottom-up approach should push to a stronger commitment by States. So far, it appears to be a winning bet: around sixty States made commitments in 2009 and 2010, whereas 177 have signed the Paris Agreement[4].

POLITICAL AGENDA SETTING – GETTING ON TO THE POLITICAL AGENDA

The political agenda is defined by Garraud (in Hassenteufel, 2010) as "*a set of problems subjected to treatment of any kind by the political authorities, and therefore likely to be the object of one or several political decisions*". In other words, the political agenda is composed of all subjects likely to be object of political decisions.

Tough competition for the political agenda

At both the national and international level, problems face strong competition to get on the political agenda. All subjects cannot be on the agenda. At their origin, subjects are not public: they must be constructed as such. For instance, all citizens are not *a priori* concerned by sea-level rise, and thus it is not perceived as a societal or public problem. The actors concerned by this question (civil society, associations, businesses, political parties, for instance) may mobilise and reconstruct the perception of sea-level rise as to make it a public problem. They can show the impacts of the phenomenon on water and food resources, or the consequences on the country's economy and civil society. Sea-level rise then becomes a problem that is constructed as public. Considering the over-abundance of problems competing for the political agenda, a choice must be made. Hilgartner and Bosk (1998) consider that "*public attention is a rare resource […], problems must strive to occupy space in the public arena*"[5]. This competition is constant, whether to gain access to or to stay on the political agenda.

Environmental policy is no exception to this rule. Competition between subjects, or problems, impacts the topics addressed in States' INDCs.

The definition of national interest in environmental terms

State delegations are mandated to define and defend their national interest at the international level. A State's interest, and thus position during international negotiations, depends mainly on two independent variables according to the principle of rationality of States (Morin and Orsini 2015).

The first variable is the country's vulnerability, meaning the extent of environmental damage a State, its population or its territory is subjected to. Logically, the greater the damage a State is subjected to because of a certain problem, the more it will try to combat this problem. The second variable is the abatement costs, or the replacement of equipment, the development of new technologies, the abandonment of other technologies and old *modus operandi*. It is not rational for a State to adopt a solution if the cost of this solution is excessive in regard to the problem.

4 http://www.cop21.gouv.fr/un-record-plus-de-160-pays-attendus-a-new-york-le-22-avril-pour-signer-laccord-de-paris, last consulted on September 20, 2016.

5 In Hassenteufel, 2010

To the contrary, if the cost is low compared to the consequences of the States' vulnerability, the country will have strong incentive to act. States undertake a cost-benefit analysis of their behavioural change depending on the information available to them. States' interests vary depending on the given environmental problem[6]. This approach to public decision analysis does not take into account other factors, such as the existence of a bureaucracy that defends its interests (survival of existing institutions), for instance. Underlying geopolitical tendencies may influence the position adopted by a State and the definition of its interest. The end of the Cold War boosted international cooperation and the proliferation of more global regimes (Terhalle and Delpledge, 2013). The rational approach nonetheless helps understand – at least in part – how a State defines its interest, and thus its behaviour on the international arena (see Fig. 1).

Windows of opportunity

John Kingdon considers that "*when a problem is acknowledged/recognized, a solution is developed and available within the public policy community, a political change creates the right moment for a policy change and that the potential constraints are not to strong*"[7], then a problem constructed as public will gain access to the political agenda.

Having identified a problem, a solution, and political will are all necessary to have a window of opportunity (a possibility to access the political agenda). This is why research should be encouraged. Indeed, research can enable the identification of a problem, and can even offer concrete answers on the origins of said problem. Exploring solutions should also be a priority for researchers and other mobilised actors, if they hope to see their problem attain the political agenda. Political will can draw its source from a strong mobilization of the civil society, election day, or even a striking event, such as a tropical storm. Without political will, decision-makers are less likely to listen to research results.

THE OCEAN IN MEDITERRANEAN STATES' NATIONAL CONTRIBUTIONS

The ocean: an irreplaceable and precious resource

An (over)exploited resource

For all the Mediterranean States, the ocean is a source of income. Finding exact data on the percentage of GDP that comes – either directly or indirectly – from the ocean proves difficult. Undeniably, seaside tourism, fishing, and maritime transportation amongst others, are profitable sectors. However, these activities generate stress on their environment: overfishing, pollution, excessive urbanisation, over-exploitation of water resources. Yet, in arid and semi-arid countries, water is a valuable resource, that the ocean can supply thanks to desalinization. This accentuates stress on the natural environment. In half of the Mediterranean States' INDCs (Egypt, Israel, Morocco, Tunisia), desalinization is mentioned as both a current and future resource. Israel wishes to use this technique to cope with a raise in water demand. Morocco hopes to increase its water resources before 2030. Tunisia plans

6 For instance, the Moroccan contribution explains that the country "*must focus on minimising the risks of climate change impacts. Certain economic activities, such as agriculture, fisheries, aquaculture, forestry and tourism are significantly vulnerable, as are certain ecosystems, such as oases, the coast and mountains.*"
7 Translated from English to French by Hassenteufel and from French to English by the author.

Behaviors expected from States depending on their interests		Degree of Vulnerability: Low	Degree of Vulnerability: High
Abatement cost	Low	Spectator	Promotor
	High	Obstructionnist	Intermediate

Fig.1 — Source : Sprinz et Vaahatoranta, 1994 in Morin and Orsini 2015.

to install small desalination plants to accommodate local needs in touristic zones[8].

Indirect stress factors

The Mediterranean also endures indirect pressure. Due to desertification and loss of arable lands, certain rural populations are forced into exodus towards urban centres, often located on the coast. Meanwhile, the population grows, on average, 1,4% per year in Mediterranean States (excepted European Union). These countries are facing strong demographic stress, generally on the coastline. The Mediterranean basin faces another pressure: pollution from industries, agriculture, cities and tourism flows directly into marine ecosystems.

8 INDC Israël, Morocco, Tunisia

Challenges and solutions in the Mediterranean

The ocean as a source of vulnerability

Most of the Mediterranean States undertake a situational analysis of their national circumstances (political, economic and social context) because the consequences of climate change are adding onto an already fragile national context. For instance, Lebanon recalls its regional political agitation, high poverty levels and the 30% increase of its

	GDP per habitant 2011-2015	Land and marine protected zones (percentage of national territory)	Annual population growth, percentage	Length of coastline (in km)	Land borders (in km)	Average elevation (m)	Percentage of territory that is under 5m elevation (percentage)	Total words concerning the ocean
Algeria	5484,1 $	7,5	1,9	998	6734	800	0	6
Egypt	3365,7 $	9,6	2,2	2450	2612	321	1,6	24
Israel	37206,2 $	8,6	1,9	273	1068	508	0,4	5
Lebanon	10057,9 $	0,9	1,2	225	484	125	0,4	14
Morocco	3190,3 $	20,1	1,4	1835	2362,5	909	0,2	17
Monaco	163651,6 $	99,7	0,3	4,1	6	NA	25,3	1
Tunisia	4420,7 $	3,7	1,0	1148	1495	246	1,9	29
Turkey	$10515,0 $	0,2	1,2	7200	2816	1132	0,5	2

Data from the CIA Factbook and the World Bank

To quantify the integration of the ocean in Mediterranean States' INDCs (excluding the EU, Syria and Libya), key words in relation to the ocean were counted. The chosen words are the following: adaptation, acidification, aquaculture, biodiversity, blue carbon, blue economy, coast, coastline, coastal, coral, deoxygenation, desalinization, ecosystem(s), fishery(ies), marine, maritime, mangrove, marsh, mitigation, ocean warming, offshore, reef, sea-level rise . These words were essentially chosen in the Ocean and Climate Platform's policy reccomendations.

Tunisia is at the top of the rankings, with these words coming up 29 times (excepted adaptation and mitigation), closely followed by Egypt (24), Morocco (17 and Lebanon (14).

The European Union, Syria and Libya are not taken into account because they do not have a national contribution . The European Union submitted a group contribution for all its Member States. In regard to their political, economic and social circumstances, Syria and Libya have not written a contribution.

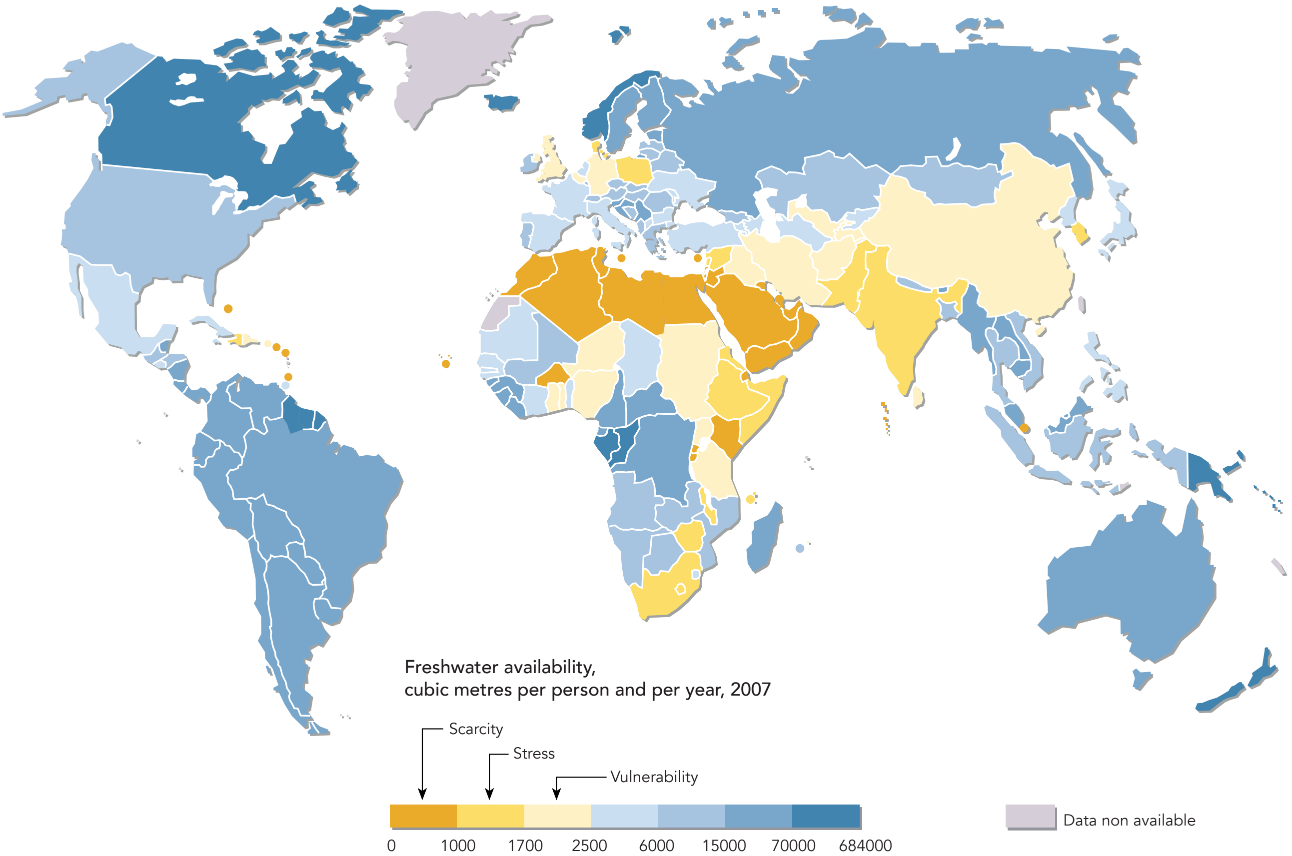


Fig.2 — Freshwater availability, cubic metres per person and per year, in 2007. Source: FAO, United Nations, World Resources Institute (WRI), Designer: Philippe Rekacewicz 2008).

population between 2013 and 2015 due, namely, to the Syrian refugee crisis. According to the Lebanese INDC, these factors intensify stress on an economy and on natural resources that are already under pressure[9].

Yet, Middle Eastern and Southern Mediterranean countries have a distinctive feature: they are located in the only region in the world that lacks water[10] (see Fig. 2). Climate change will deeply affect coastlines and water distribution. Sea-level rise will have a direct effect on an invaluable resource: fresh water. Salt-water intrusion is a major concern for countries such as Tunisia and Egypt, where more than 1,5% of national territory is located under 5m of altitude. The Tunisian contribution states that 50% of its water resources in coastal groundwater risks salinization. The rise of sea-level also salinizes arable land.

In addition to deteriorating resources as basic as water and food, sea-level rise damages sea-side infrastructures, including touristic and port infrastructures, or even power plants, impairing the countries' economy. Displacement of populations is another consequence of this phenomenon. For instance, in Algeria, over 85% of the population lives in the North of the country, so on the coast. Major cities such as Alexandria or Port Saïd in Egypt will eventually be flooded. These huge population flows would further destabilise the country[11].

Sea-level rise obliges States to adapt their tourist-economy so as to continue to benefit from the sector. Seaside tourism generates a large income: 90% of tourism in Tunisia is coastal, 80% in Lebanon, and 80% in Israel. In 2015, 11,4% of the Egyptian GDP was generated by

9 *"To exacerbate matters, the Syrian crisis has led to the arrival of around 1,13 million registered refugees to the country, increasing Lebanon's population by 30% in just over 2 years and adding stress to the already-stretched economy and natural resources"*. INDC Lebanon.

10 According to the Falkenmark index.

11 *"Estimations indicate that sea-level rise by 50cm leads to serious impacts on low-level lands in Delta and highly populated cities such as Alexandria and Port Saïd. Consequently, this will result in a more significant challenge, which is the migration of people from the affected areas to other areas, thus affecting the efficiency of different services and increasing the financial cost required for their development."* Egyptian Arab Republic INDC.

tourism, 35% of which was on the seaside. Coral reefs – Egypt's 4th touristic sector – are highly vulnerable to climate changes.

The ocean's temperature is also rising, disturbing the distribution of marine species and displacing fish stocks. This provokes heavy repercussions on the fishing industry. Touristic destinations can become less attractive due to a rapid proliferation of harmful algae, which is stimulated by the increase in temperatures. Economical vulnerability of coastal regions is a recurring theme in contributions that mention the ocean.

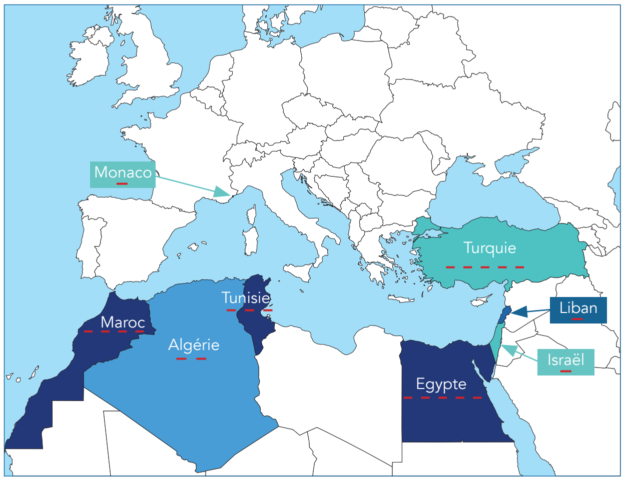
A tool to be developed

Many countries consider themselves vulnerable to the ocean. However, the ocean can also be a source of adaptation and mitigation to better cope with climate change.

Planned management of the coast helps avoid excessive and un-orderly urbanisation while putting a priority on zones that are less prone to flooding and erosion. Egypt and Morocco both propose this type of solution[12].

In terms of mitigation, marine renewable energies can help reduce dependency to flared gas or fossil energy. Reforestation can also help limit coastal erosion at a lower cost. Morocco plans to reconvert nearly 1 million hectares of cereal production to fruit tree plantations, which would protect farmlands from erosion[13].

Therefore, it appears that States including the ocean in their INDCs are those whose economy and society will be most affected by climate change. Egypt and Tunisia depend on seaside tourism, and have many farmlands, cities and aquifers that will potentially be flooded in the coming decades, affecting the heart of their economies. It is in these States' interests to act, taking into account the ocean in their national contributions.



Longueur du trait de côte (km)	
1-500	–
501-1000	– –
1001-1500	– – –
1501-2000	– – – –
>2001	– – – – –

Nombre de mots liés à l'océan	
1-5	
6-10	
11-15	
>15	

Fig.3 — Number of ocean-related words in Mediterranean INDCs compared to the length of their coast, in 2016. © Léa Lebechnech.

YOUTH FOR OCEAN !

French American Climate Talks on Ocean

ocean-climate.org

12 Morocco has already undertaken a « *National Strategy for Integrated Coastal Management* ». Egypt is also putting forward integrated coastal management (« *Adaptation options for coastal zones are highly site-dependent. However, changes in land use, integrated coastal management, and proactive planning for protecting coastal zones are necessary adaptation policies.* » INDC Egypt).
13 The Marrocan contribution mentions a « *conversion of nearly one million hectares of grain crops to fruit plantations that are likely to protect agriculteral areas from all forms of erosion, especially water erosion* ».

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REFERENCES

- BANQUE MONDIALE – http://donnees.banquemondiale.org/pays.
- BENBLIDA M., 2011 – *L'efficience d'utilisation de l'eau et approche économique*. Etude nationale, Algérie, Plan Bleu, Centre d'activités régionales PNUE/PAM.
- CIA WORLD FACTBOOK – https://www.cia.gov/library/publications/the-world-factbook/index.html.
- COP21 – *Fiche d'analyse contributions nationales.* Dossier de presse, cop21.gouv.fr.
- COP21 – http://www.cop21.gouv.fr/un-record-plus-de-160-pays-attendus-a-new-york-le-22-avril-pour-signer-laccord-de-paris, consulté en septembre 2016.
- DIERMEIER D., 2012 – *Institutionalism and the Normative Study of Politics: From Rational Choice to Behavioralism.* The Good Society, Vol 24 n°1, pp.15-29.
- GRIMES S., 2011 – *Profil de durabilité dans quelques destinations touristiques méditerranéennes.* La destination touristique pilote en Algérie : la zone côtière de Tipasa, Plan Bleu, Centre d'Activités Régionales PNUE/PAM.
- HASSENTEUFEL P., 2010 – *Les processus de mise sur l'agenda : sélection et construction des problèmes publics.* Informations sociales, n°157, pp. 50-58.
- IDDRI BLOG – *Les INDC, nouveaux outils de coopération internationale pour le climat.* www.blog-iddri.org/fr/2015/03/26/les-indc-nouveaux-outils-de-cooperation-internationale-pour-le-climat.
- ISRAEL MINISTRY OF FOREIGN AFFAIRS – http://mfa.gov.il/MFA/AboutIsrael/Economy/Pages/ECONOMY-%20Sectors%20of%20the%20Economy.aspx.
- MORIN J-F. and ORSINI A., 2015 – *Politique internationale de l'environnement.* Paris, Presses de Sciences Po (P.F.N.S.P.), « Les Manuels de Sciences Po ».
- OCEAN AND CLIMATE, 2015 – *Policy recommendations*, 8 pages.
- Plan Bleu, 2015 – *Recommandations pour l'analyse économique et sociale des écosystèmes méditerranéens.* Préparées pour les pays méditerranéens non membres de l'UE dans le cadre de la mise en ouvre de la feuille de route EcAp du PAM, version révisée.
- TERHALLE M. and DEPLEDGE J., 2013 – *Great-power politics, order transition, and climate governance: insights from international relations theory.* Climate Policy.
- TRESOR DIRECTION GENERALE – www.tresor.economie.gouv.fr/13892_point-sur-le-tourisme-en-egypte-.
- UNEP – http://www.unep.org/dewa/Africa/publications/AEO-1/148.htm.
- UNFCCC – http://unfccc.int/focus/indc_portal/items/8766.php.
- UNFCCC – http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx.
- WORLD RESOURCES INSTITUTE – http://www.wri.org/indc-definition.
- WORLD RESOURCES INSTITUTE, 2015 – *Decoding intended nationally determined contributions (INDCS): A Guide for Understanding Country Commitments.*

Which International Law for Ocean and Climate?

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The United Nations Convention on the Law of the Sea (UNCLOS) and the United Nations Framework Convention on Climate Change (UNFCCC) shape the legal backbone of sea and climate law on the international level. Framework conventions mark the beginning of specific legal systems that are destined to evolve. The UNCLOS takes into account only in an incidental manner certain aspects affecting climate in relation to the ocean. Climate change creates new challenges for the Law of the Sea, which then must adapt to tackle its impacts and showcase the ocean's "regulating" role. Regulation of GHG emissions in maritime transport, ice-melt in the Arctic, or even sea-level rise has become the object of international discussions and calls for further legal development. To affirm that the ocean has been completely left out of international climate negotiations would be at very least imprecise. The ocean was inderectly mentioned at several occasions during debats and in international texts. These references are incomplete and the relative legal provisions suffer from a limited legal scope. The effects of scientific and political mobilization concerning the links between ocean and climate set conditions for a consolidation of the integration of the ocean in climate law. The inclusion of the term "ocean" in the Paris Treaty, the IPCC special report on *"Climate change and the oceans and the cryosphere"*, or the existence of an ocean session at COP22 – where the implementation of the treaty will be discussed – all foretell a strengthening of the ocean in the climate regime.

INTRODUCTION

The United Nations Convention on the Law of the Sea (UNCLOS) and the United Nations Framework Convention on Climate Change (UNFCCC) respectively form the framework of the Law of the Sea and the Law of Climate at the international level. As framework agreements, they are the starting point of new specific legal regimes which are intended to evolve over time.

The UNCLOS, which was signed on the 10th December 1982, is the result of the codification process of the Law of the sea, but also of the formation of new legal rules (*e.g.*, the Exclusive Economic Zone (EEZ) or the status of archipelagic States). The "constitution for the oceans"[1], convention which has almost a universal scope (167 States Parties in 2016), establishes the general framework within which maritime activities take place (navigation, exploitation of biological and mineral resources, conservation and preservation of the marine environment, marine scientific research, etc.). It defines the rights and obligations of States conducting such activities according to the subdivision of Oceans and Seas in areas under the sovereignty or jurisdiction (internal waters, territorial

1 Expression formulated by Tommy T.B. KOH (Singapore), President of the third United Nations Conference on the Law of the Sea: "A constitution for the Oceans", 11 December 1982, 5 p.; online: http://www.un.org/depts/los/convention_agreements/texts/koh_english.pdf (last consulted, August 2016).

sea and contiguous zone, EEZ, continental shelf) and spaces beyond the limits of national jurisdiction (High seas, the Area)[2].

Since it came into force on the 16th November 1994, more than ten years after its signature in Montego Bay (Jamaica), the International Community has shown a growing concern for many issues related to the uses of Seas and Oceans and the protection of the Marine Environment. The topics of major concern are the decrease in fisheries stocks, the destruction of marine and coastal habitats, the sustainable use of biological resources and the conservation of marine biodiversity, the uncontrolled pressure of urbanization and tourism, the pollution resulting from land and sea activities and, for about a decade, the interrelations between Climate Change and Ocean.

At the end of the 1980s, the threat of global warming began to preoccupy States in a scientific context enabling a holistic understanding of the Environment. This issue requiring cooperation of all States, meetings of experts (experts of the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO)), international conferences (Ottawa and the Hague (1989)) and resolutions of the General Assembly of the United Nations (in particular, Resolution 43/53: Protection of global climate for present and future generations of mankind, December 6, 1988), the development of a draft framework convention on climate change progressed towards the adoption of the final text on the 9th May 1992 in New York and its opening for signature the same year at the Earth summit in Rio de Janeiro[3].

Universal in scope (197 States Parties in 2016), the UNFCCC which came into force the same year as the UNCLOS in 1994 (21st of March), is the cornerstone of the climate regime. Its title is misleading because it suggests that it applies to each "Climate change" as it only considers change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere at global level (art. 1, § 2)[4]. Its objective is the "*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*"[5] (art. 2). It was complemented by the Kyoto Protocol on Climate Change of the 11th December 1997 (entered into force on the 16th February 2005) counting 192 States Parties and the Paris Agreement on climate signed on the 22nd of April 2016 by 175 States.

Beyond their goals, their contents and the context of their negotiation, the UNCLOS and the UNFCCC differ ideologically and politically, in their understanding of global environmental issues. While the UNCLOS considers the Area as a common Heritage of Mankind (art. 136), the UNFCCC marks an ideological retreat by making Climate Change only a Common Concern of Mankind (preamble), a concept which has no legal force.

For now, and as we will see through the respective consideration of Ocean and Climate under the Law of the Sea and the Climate Law, the response of the international community to global environmental challenges is still limited in Law and Practice; but these challenges require urgent and compelling answers on all scales.

CLIMATE IN THE INTERNATIONAL LAW OF THE SEA

The UNCLOS makes no explicit reference to Climate Change. Given its purpose, it takes into account only incidentally specific aspects of Climate in its relations with the Ocean. However, in recent years, Climate Change has emerged as an issue which goes beyond the framework of the climate regime, leading

2 For a mapping of maritime delimitations, see AGENCES DES AIRES MARINES PROTEGEES: Les délimitations de l'espace maritime francais, November 2014, p. 2; online: http://carto- graphie.aires-marines.fr/sites/default/les/delimitations_espace_maritime_fr.pdf (latest consultation in August 2016)

3 See, BEURIER (J.-P.), KISS (A.†): Droit international de l'environnement, Paris, éd. Pédone, coll. Études internationales, 2010, p. 264 et s.

4 BEURIER (J.-P.), Kiss (A.†) : Droit international de l'environnement, Paris, éd. Pédone, coll. Etudes internationales, 2010, p. 265.

5 Also, Parties States to the UNFCCC have a shared responsibility to preserve the climate system in the interest of present and future generations, on the basis of equity and depending on their common but shared responsibilities. States may take into account special needs and the specificities of developing countries circumstances, but it is also necessary to take precautionary measures to foresee and mitigate the causes of climate change and limit their harmful effects (art.3).

lawyers and policy makers to pay more attention to this central issue of the Ocean Governance. The Law of the Sea now faces the challenge of adapting to fight against Climate Change and to highlight the "regulating" role of the Ocean.

The incidental consideration of certain aspects pertaining to climate in the UNCLOS[6]

Climate change was not discussed at the third UN Conference on the Law of the Sea (1973-1982), at a time when it was not on the international environmental agenda. If the UNCLOS does not directly address the climate issue, it can be interpreted and applied so as to grasp climate change, in particular through its provisions on *Protection and Preservation of the marine environment* (Part XII) and on *Marine Scientific Research* (Part XIII).

The Protection and the Preservation of the Marine Environment, including the climate perspective

Although the UNCLOS remains silent about climate change and Greenhouse Gas emissions (GHG), the provisions of Part XII entitled "*Protection and preservation of the marine environment*" are relevant to address these issues. Article 192 thus provides that "*States have the obligation to protect and preserve the marine environment*", including "*rare or fragile ecosystems as well as the habitat of depleted, threatened or endangered species and other forms of marine life*" (art. 194.5). This general obligation may well apply to ecosystems such as coral reefs and species affected by climate change, particularly global warming and ocean acidification.

The obligation to protect and preserve the marine environment is supplemented with other provisions to tackle marine environment pollution, which includes general measures to prevent, reduce and control pollution whatever the source (art. 194), and specific measures such as, measures to combat pollution from land-based sources (art. 207), pollution by dumping (Art. 210), pollution from vessels (art. 211) and pollution from or through the atmosphere (art. 212). If GHG emissions are not specifically mentioned in the UNCLOS as a source of pollution of the marine environment, it is quite possible to interpret Part XII to include this type of pollution.

Indeed, the UNCLOS provides a broad definition of marine pollution, i.e. "*the introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities*" (art. 1. (1) 4.).

Therefore, the question arises whether the violation of the general and specific obligations of States to protect and preserve the marine environment could be invoked in the light of climate change under the dispute settlement mechanism provided for in Part XV of the UNCLOS. Even if the doctrinal debate on this point is rich, the question remains open. Only the future will tell whether the UNCLOS is able to grasp and respond to the new challenges posed by climate change and above all, all to make any coercive responses.

The obligation for States and International Organizations to promote Marine Scientific Research, including about ocean-climate interactions

The UNCLOS provides in Part XIII on Marine Scientific Research an innovative legal regime governing research activities carried out by States and international organizations such as the WMO and the UNESCO Intergovernmental Oceanographic Commission (UNESCO-IOC), anywhere at sea. This regime includes, *inter alia*, a focus on the need to promote marine scientific research (art. 243 et seq.) and international cooperation in this field (art. 242).

Under these provisions, much research has been conducted in the marine realm with the aim to better understand the impacts of climate change on the ocean and particularly, marine biodiversity.

6 Text of the UNCLOS available online: http://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_f.pdf (last consultation in August 2016)

For example, scientists of the Tara expeditions are addressing the role of microscopic marine biodiversity and its interaction with climate[7]. But the more research progresses, the more obvious the lack of knowledge becomes, requiring urgent strengthening of scientific, technical and financial capacities.

In recent years, the United Nations General Assembly has recognized the need to improve the understanding of the impact of climate change on the oceans. It encouraged States to enhance their scientific activity to better understand the effects of climate change on the marine environment and marine biodiversity and develop ways and means of adaptation[8]. It also stressed the importance of increasing scientific knowledge of the interrelations between the oceans and the atmosphere, through the participation in ocean observing programs and geographic information systems, such as the Global Observation Observing System[9].

Climate change: a core challenge for ocean governance

The impact of climate change on the marine environment, unlike forest ecosystems, has belatedly attracted the attention of the international community despite the increasingly numerous and reliable scientific data. Scientists have shown that the ocean is a regulator of global climate: it is a natural sink and a GHG reservoir and it receives almost all of the water released by the melting of continental glaciers and polar caps[10]. It was only in the 2000s that this issue was seen to be crucial, involving the international community as a whole and not only some coastal and archipelagic States which are particularly vulnerable.

Climate change is a core challenge, at the interface between a plurality of activities (shipping, fishing, exploitation of mineral resources, marine scientific research, etc.), actions (fight against poverty, natural disasters, pollution, biodiversity erosion, etc.) or issues (maritime boundaries, access to natural resources, protection of the marine environment etc.), already taken into account by international Law. They also raise new issues such as the impact of climate change on marine biodiversity, the regulation of shipping GHG emissions, geo-engineering activities in the oceans, issues that may require the establishment of specific legal rules. We will consider below some current examples.

Sea-level rise: modification of maritime borders and likely disappearance of States

Sea-level rise impacts maritime boundaries whose stable delimitation is still one of the main purposes of the international Law of the Sea and the UNCLOS. The lines of maritime boundaries delimitation, as well as baselines would be called into question, as well as the principle of sovereignty over land territory which gives rights to States on adjacent marine territory (the land dominates the sea). Thus, "*shifting baselines*"[11] resulting from sea-level rise will introduce a modification of the marine spaces of some coastal and archipelagic States (territorial sea, contiguous zone, EEZ and continental shelf). That will undoubtedly create tension between States, especially between neighbouring States, in delimitation of national maritime boundaries, access to natural resources and navigation.

In the most extreme cases, sea-level rise will mean the disappearance of coastal and low-lying islands which will be submerged or rendered uninhabitable by lack of access to natural resources, particularly water, or because of natural disasters becoming

7 For more information, see the official website of Tara Expeditions : http://oceans.taraexpeditions.org/ (last consultation in August 2016).

8 In particular, it has encouraged States and competent International Organizations to urgently pursue further research on ocean acidification, especially programs of observation and measurement (See. Resolution 64/71, § 113).

9 See Resolution 64/71, § 169.

10 The impacts of climate change on the marine environment were scientifically proven in the early 1980's. Scientific data shows important disruptions in the physical and chemical parameters of the global ocean: ice-cap, iceberg, glacier, and sea ice melting; sea-level rise; acidification; deoxygenation; disruption of marine currents; erosion of biodiversity; release of methane in the water and the atmosphere. These radical environmental changes combine the ones with the others, as well as with other anthropogenic stress on the marine environment (pollution, overexploitation of natural resources, destruction of habitats, tourism, etc.). They are capable of producing runaway phenomena.

11 ORELLANA (M. A.): Climate change and the international Law of the Sea, in ABATE (R. S.) (dir.): Climate Change Impacts on Ocean and Coastal Law: U.S. and International Perspectives, New York (États-Unis), éd. Oxford University Press, 2015, p. 256 et s.

more frequent (floods, tsunamis, cyclones, etc.). The example of the Small Island States of the South Pacific is the most eloquent. This raises the thorny legal, political and humanitarian issue of the loss of Statehood and population migration, climate or environmental refugees, which it entails.

The melting of arctic ice: the opening of new regular shipping routes and ways to access natural resources

The end of the Soviet Union and global warming have changed the perception of States and ship-owners alike about the three arctic polar routes, namely the Arctic Bridge between Churchill (Hudson Bay) and Murmansk (White Sea) and the Northwest and Northeast passages. If the Arctic bridge is not subject to specific legal issues, the two passages raise economic, geopolitical, strategic and environmental concerns related to the opening of new regular shipping routes and access to natural resources caused by melting ice which require binding legal solutions.

The different positions of States on the Northwest Passage are an example[12]. Indeed, the riparian and non-riparian States of this passage already crossed by icebreakers and submarines remain divided on the legal status to be granted. The Canadian State thus considers that this passage is within its internal waters as it wishes to preserve strategic areas and the marine environment, while the United States believes that this passage is an international strait open to navigation on the principle of free transit passage according to Part III of the UNCLOS[13].

On the 11th January 1988, Canada and the United States signed an agreement in Ottawa on cooperation in the Arctic by which the United States, while refusing to recognize Canadian claims, agreed that the movements of their icebreakers crossing in the Northwest will be subject to the consent of the Canadian authorities. On the 19th June 1992, in Ottawa, Canada signed with the Russian Federation a new agreement on scientific cooperation explicitly considering the Arctic as a special area. Since then soft law on navigation and protection of the marine environment has been added to these binding rules[14].

Given the fragile polar ecosystems, the UNCLOS envisages the possibility for coastal States "*to adopt and enforce non-discriminatory laws and regulations for the prevention, reduction and control of marine pollution from vessels in ice-covered areas within the limits of the exclusive economic zone, where particularly severe climatic conditions and the presence of ice covering such areas for most of the year create obstructions or exceptional hazards to navigation, and pollution of the marine environment could cause major harm to or irreversible disturbance of the ecological balance […]*" (art. 234). The impact of climate change in the Arctic requires the urgent establishment of a specific binding multilateral agreement. It could follow the model of the regional seas conventions and the global-regional approach developed by the UNEP.

The regulation of GHG emissions from ships

GHG emissions from ships are a major challenge for the Law of the Sea. Considering the importance of this mode of transport in world trade – more than 80 % of trade is carried by sea nowadays – the Law of the Sea must grasp and regulate these emissions in order to fight in its turn against climate change. In this sense, the International Maritime Organization (IMO) through its Marine Environment Protection Committee (MEPC) has recently laid the groundwork for international regulation of control and reduction of GHG emissions from shipping. IMO is the specialized agency of the United Nations responsible for establishing standards for safety, security and environmental performance of international shipping. It ensures a general fight

12 From a commercial standpoint, this reduces the distance covered by commercial ships going through the Panama Canal by about 1 000 mn, and would significantly reduce the cost of transport. In September 2013, the MS Nordic Orion, a bulk carrier flying the Panama flag, was the first large cargo ship to take this route. From an environmental perspective, the risk of mishaps related to navigation in the fragile Arctic ecosystems are a major source of concern. From a geopolitical perspective, the transit of pirates, terrorists, or other unlawful groups, through the Arctic is another source of concern: ORELLANA (M.A.): Climate change and the international Law of the Sea, in ABATE (R. S.) (dir.): Climate Change Impacts on Ocean and Coastal Law: U.S. and International Perspectives, New York (États-Unis), éd. Oxford University Press, 2015, p. 267.

13 For more information, see BEURIER (J.-P.) (dir.): Droits maritimes, Paris, éd. Dalloz, coll. Dalloz action, 2015-2016, p. 128 et s.

14 V. BEURIER (J.-P.) (dir.): Droits maritimes, Paris, éd. Dalloz, coll. Dalloz action, 2015-2016, p. 132.

against marine pollution by ships. Its main role is to create a fair and effective regulatory framework for the shipping sector, and which is adopted and implemented universally[15].

At its meeting on the 18th and 22nd April 2016, the MEPC has adopted a regulation requiring all ships over 5,000 gross tonnage to measure their CO_2 emissions and to report to IMO. This regulation is the cornerstone of a larger edifice aiming at a real reduction in GHG emissions from merchant ships. Following this line of thought, IMO stressed the importance of adopting an international convention on the reduction of shipping 's CO_2 emissions in line with the Paris Agreement.

OCEAN IN INTERNATIONAL CLIMATE LAW

It would be inaccurate to assert unconditionally that the ocean is the great forgotten element in international climate negotiations. On several occasions in debates and in international documents, the Ocean was referred to as one aspect of the fight against climate change. However, analysis of positive law reveals that only timid steps have been taken, whereas the seas and oceans represent 71% of the Earth's surface and absorb more than 25% of the CO_2 emitted annually by Mankind. However, an analysis of the effects of scientific and political mobilization around the interrelationship between ocean and climate indicates that the ocean will become increasingly integrated into climate Law in the future and for COP22.

The timid consideration of the Ocean in the climate regime

The UNFCCC makes no reference to the UNCLOS. It does not highlight explicitly the relations between the two conventions. A lack of mutual recognition of the two legal corpuses may be observed. The synergies between these two legal corpuses have not been highlighted, indicating a limited consideration of the Ocean in the climate regime.

15 Definition from the IMO website: http://www.imo.org/fr/About/Pages/default.aspx

A partial recognition

The climate regime refers to the ocean through the "narrow prism" of natural sinks and reservoirs of GHG. This almost exclusive approach reflects the importance that the ocean plays in climate regulation. It absorbs most of the heat and carbon dioxide that is accumulated in the atmosphere. It has absorbed 93% of the excessive heat on Earth since the 1970s and thus limits the warming of the atmosphere. It has trapped 28% of CO_2 emissions of anthropogenic origin since 1750.

The consideration of the ocean within the climate regime has thus been clearly identified through the prism of sink as well as of reservoir. Excepted the Paris Agreement which represents a step forward on this, as well as quick reference to marine ecosystems in the UNFCCC text, the ocean has always been approached from this angle. There have been countless provisions on the protection and reinforcement "*sinks and greenhouse gas tanks*"[16]. In this way, all the issues related to the ocean as such have been relegated to the background or even ignored. Designating the ocean directly in these texts, as well as provisions taking into account all the ocean-climate relations, it would gain greater legal force, like forests that benefit from a real consideration.

A weak legal recognition

The legal provisions on the ocean, whether they are explicit or not, enjoy only relative significance. The fact that the ocean is included residually or conditionally in the texts relating to climate demonstrates limited legal force. The ocean has for example been explicitly named in the Paris Agreement but only in its preamble which, in the general spirit of the text, mentions the main objectives of the States Parties. A

16 Art 4 of the UNFCCC on the commitments and §4 of the preamble make reference to this. The text of the UNFCCC is available online: http://unfccc.int/resource/docs/convkp/ convfr.pdf (last consultation in August 2016). The Kyoto Protocol makes reference to "sinks and greenhouse gas tanks" in articles 2-1.A)ii; 3-3; 3-4; 3-7; 5-1; 5-2; 5-3; 6-1; 7-1; 10-1 a); 10-1 b)ii). The text of the Kyoto Protocol is available online: http://unfccc.int/resource/docs/convkp/kpfrench.pdf (last consultation in August 2016). The Paris Agreement makes reference to this in its preamble and in its article 5-1. The text of the Paris Agreement is available online: http://unfccc.int/ resource/docs/2015/cop21/fre/l09r01f.pdf (last consultation in August 2016)

preamble, which has less legal value than the Treaty, contains provisions that are too general to be applied and does not include any obligation or commitment. Thus, even when the ocean is apprehended as such, it does not benefit directly from a binding provision and its legal recognition is diminished.

Moreover, the provisions for the ocean, whether they do so explicitly or not, often use a loose terminology. Thus, the Paris Agreement says that the parties "should" take protective measures for sinks or GHG. The use of the conditional implies that this provision was not highly binding so that its breach would not result in sanctions. Similarly, if the Paris Agreement rises to the rank of an international treaty, such provisions will be difficult to enforce. Ultimately, the protection of the ocean as sinks or reservoirs would be only a possibility, one example of triggering for action on which States can build to implement treaties. This is surprising since, at the same time, science proves that the ocean is a real climate regulator. This *hiatus* between the international governance of climate and ocean on one hand and the scientific findings and the world reality on the other, shows a "*schism with reality*"[17].
In short, it is not so much the absence of the ocean in the climate regime which is observed, but the lack of overall treatment and effectiveness of the specific legal provisions applicable. This lack could be explained in particular by a weak mobilization of political and scientific communities on these issues. This is no longer the case today. The action of the Ocean and Climate Platform for example nourishes the scientific and citizen debate around the interactions between ocean and climate.

Towards a greater emphasis on the ocean by climate law?

The mobilizations of civil society and the scientific community at COP21 allowed a notable advance of the consideration of the ocean by the international climate governance.

The Paris Agreement on climate

The Paris Agreement adopted on the 12th December 2015 indeed laid the foundation for a stronger integration of the ocean by the climate regime. Almost twenty five years after the signing of the UNFCCC, it allows a renewal of how the ocean is considered by the climate regime as long as there is an explicit reference, as such. Certainly, this agreement does not provide for monitoring or enforcement mechanisms and too often includes general provisions to be enforceable by States. Eschewing a purely binding text, based on clear and precise measures, complemented by monitoring mechanisms, the Paris Agreement is based on voluntary contributions, as well as on the general objectives. That said, this legal technique has greater flexibility, adaptability and malleability. Proponents of this approach defend the idea that it has the advantage of being more realistic and therefore more effective. Thus, since the States referred explicitly to the ocean in an agreement of such political force, it will surely be more difficult for them not to take it into account in their national policies.

The future IPCC special report on climate change the oceans and the cryosphere

The lack of consistency of international Law must not, however, appear to foreshadow a disappointing legal future. The future Intergovernmental Panel on Climate Change (IPCC) report and the nebula of relevant scientific work could influence climate change Law. The IPCC has decided at its 43rd plenary session in April 2016, to devote a special report to the interactions between climate change, the oceans and the cryosphere[18].

The operation of the IPCC and the scope of its work suggest development in the near future as the consideration of the ocean in the climate regime. The IPCC does not primarily intend to conduct research

17 AYKUT (S. C.), DAHAN (A.): Gouverner le climat ? 20 ans de négociations internationales, Chapitre 8 : Paris (France), éd. Presses de la fondation nationale des sciences politiques (SciencesPo Les Presses), coll. Références : Développement durable, 2014, p. 399 et s.

18 Presentation of the Special report of the IPCC on the interactions between climate change, the oceans and the cryosphere and sub-themes available online: https://www.ipcc.ch/report/srocc (last consultation in August 2016).

or to produce scientific content, essentially working to make a synthesis and assessment of the state of the art science on climate change. Its works are the basis for an informed policy decision. It allows to facilitate or to direct the formation of law. If the IPCC decides to focus part of its work on the ocean, we may be seeing the beginnings of a better account of the interactions between ocean and climate in the climate regime.

The 22nd Conference of Parties to the UNFCCC

The scientific community at large as well as civil society and citizens also have a proactive and complementary role to challenge the international community and policy makers on the pivotal role of the ocean to the environmental protection and climate globally. Many initiatives and projects are emerging around the world, involving multiple stakeholders (NGOs, research institutions, local communities, private companies, etc.) and more and more beyond national borders. Although multiple, this community of interest for the environmental cause carries with it the hope that at the next Conference of the Parties to the UNFCCC to be held in Marrakech (Morocco) in November, an action plan on the ocean will be discussed.

CONCLUSION

The question of whether both the international law of the sea as well as climate law will be able to face new challenges posed by climate change will be a topical issue in the 21st century. In the context of lack of capacity and the concentration of natural resources which have become scarce, the responses of International Public Law are still insufficient. They focus mostly on proposing responses to mitigate the impact of climate change on the ocean rather than considering more ambitious solutions which would imply the understanding of the ocean at international level as the global climate regulator.

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GLOSSARY

Framework convention. A framework convention is a legal technique often used by States in order to establish general rules that commit them to cooperate and to set principles of action related to a specific issue (ex: Antarctica, regional seas, climate, biodiversity), the specific implementation modalities are ultimately determined by additional protocols and national implementing measures.

International Public Law. International Public Law is defined by different criteria, the subjects that it governs, the relations that it governs or, the origin of the norms of which it is composed. According to the first criteria, International Public Law includes the legal rules, which govern the conduct of international legal subjects (States, internationals organisations, private person, etc.). According to the second criteria, International Public Law includes the legal rules governing international relations. Lastly, depending on the origin of norms, International Public Law refers to the norms from State agreements or from different entities to which States have granted the ability to establish international rules.

Law of the Sea. All rules of international law pertaining to the determination and the status of maritime areas and, to the legal regime of maritime activities.

Climate Law. All international rules aiming to foresee, prevent or mitigate the causes of climate changes and, limit adverse effects (art 3 CCNUCC); or, regulation of human activities with impacts on climate.

Legal regime. All rules that regulate a specific legal institution.

Legal effectiveness. Character that exists in fact. It is the quality of a legal situation corresponding to the reality, of a competence that is truly exercised. Effectiveness creates legal effects, in conditions determined by the international legal order itself. It thus plays a role in numerous institutions of international law.

Greenhouse gas sink. Any process, activity or mechanism that removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas from the atmosphere.

Greenhouse gas reservoir. A component or components of the climate system store greenhouse gases or precursors of greenhouse gases.

Common Heritage of Humanity. Areas or goods belonging to all of humanity and, thus excluded from States exclusive appropriation.

Party State. Quality of a State having expressed its consent to be bound by a treaty once it has entered into force.

Signing. Only the executive power can sign a treaty (head of State, head of government or minister, depending on the importance of the treaty in question). The signature of a Convention or a Protocol is equivalent to a preliminary approval. There is no executive obligation. The signature displays a State's intention to examine a treaty at the national level and consider its ratification. Although a signature is not a promise of ratification, it does bind the State to not commit acts contrary to the objectives or the purpose of the treaty.

Ratification. Ratification means that a State accepts to be legally bound by the provisions of a Convention. The State first signs the treaty, and then ratifies it. A Convention only enters into force after having been ratified by a minimum number of States (the Convention itself defines the required lower limit for its entry into force).

REFERENCES

- AYKUT S. C. and DAHAN A., 2014 – *Gouverner le climat ? 20 ans de négociations internationales.* Paris, Presses de la fondation nationale des sciences politiques (SciencesPo Les Presses), coll. Références : Développement durable, 749 p.
- BEURIER J.-P. and KISS A., 2010 – *Droit international de l'environnement.* Paris, Pédone Press, coll. Études internationales, 2010, 590 p.
- BEURIER J.-P. (dir.), 2015-2015 – *Droits maritimes.* Paris, Dalloz Press, coll. Dalloz action, 1792 p.
- BOYLE A. – *Law of the Sea Perspectives on the Climate Change.* International Journal of Marine and Coastal Law, vol. 27, Issue 4, 2012, p. 831-838.
- BUREAU DES AFFAIRES JURIDIQUES – DIVISION DES AFFAIRES MARITIMES ET DU DROIT DE LA MER (ONU),13 septembre 2010 – *Oceans and Climate Change.* New York, 7 p., www.un.org/depts/los/oceans_climate_change/oceans_climate_change_7_september_2010.pdf.
- BUREAU DES AFFAIRES JURIDIQUES – DIVISION DES AFFAIRES MARITIMES ET DU DROIT DE LA MER (ONU), 2005 – *Le droit de la mer : obligations des États aux termes de la convention des Nations unies sur le droit de la mer et des instruments complémentaires.* New York, éd. Des Nations unies, 72 p., www.un.org/depts/los/doalos_publications/publicationstexts/E.04.V.5_f.pdf.
- CÁMARA STOUGAARD-ANDRESEN R. A. – *Climate Change and the Law of the Sea.* Master thesis, Lund, éd. University of Lund, 2011, 77 p. ; en ligne: http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=1973940&fileOId=1973941
- DAILLIER P., FORTEAU M., PELLET A. and NGUYEN Q. D., 2009 – Droit international public, Paris, éd. LGDJ, coll. Traités, 8ème éd., 1722 p.
- FOYER J., 23 février 2016 – *Dans les coulisses de la COP 21, La vie des idées.* www.laviedesidees.fr/Dans-les-coulisses-de-la-COP21.html.
- HERR D. and GALLAND G. R. – *The Ocean and Climate Change: Tools and Guidelines for Action.* Gland, éd. IUCN, 72 p., https://cmsdata.iucn.org/downloads/the_ocean_and_climate_change.pdf.
- IISD, 2016 – *Climate change Policy and Practice*, http://climate-l.iisd.org.
- INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 2016 – www.ipcc.ch.
- MALJEAN-DUBOIS S. – *La mise en oeuvre du droit international de l'environnement.* Notes de l'IDDRI, n°4, 2003, 64 p., www.iddri.org/Publications/Collections/Analyses/an_0303_maljeandubois_DIE.pdf.
- MALJEAN-DUBOIS S., SPENCER T. and WEMAËRE M., 2015 – *La forme juridique du future accord de Paris sur le climat : enjeux et principales options.* Cahiers Droit, Sciences et Technologies, p. 177-208, https://cdst.revues.org/416#text.
- MBENGUE M.M., 2010 – *Le GIEC : De l'expertise ex post à l'expertise ex ante en matière de protection internationale de l'environnement.* In *Actes du colloque de la SFDI : le droit international face aux enjeux environnementaux*, Paris, éd. Pédone, 490 p.
- ORELLANA M. A., 2015 – *Climate Change and the International Law of the Sea.* In ABATE R. S. (dir.) – *Climate Change Impacts on Ocean and Coastal Law: U.S. and International Perspectives*, New York, éd. Oxford University Press, p. 253-271.
- SALMON J. (dir.), 2001 – *Dictionnaire de droit international public.* Bruxelles, éd. Bruylant, coll. Universités francophones, 1198 p.
- SOUTENBURG J. G., 2011 – *Implementing a New Regime of Stable Maritime Zones to Ensure the (Economic) Survival of Small Islands States Threatened by Sea-Level Rise.* International Journal of Marine and Coastal Law, vol. 26, Issue 2, p. 263-311.

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Ocean and Climate Platform

Involving the Ocean in the debate on Climate Change

Launched at UNESCO in June 2014, the Ocean and Climate Platform is a multi-stakeholder structure including members of the scientific community, non-profit organizations and business organizations that are all concerned about the ocean. It aims to place the ocean at the heart of international climate change debates, particularly at the COP22 in Marrakech.

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.

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