Small Islands, Ocean and Climate

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

Regardless of their political status, small islands, whether isolated or part of an archipelago[1], have to face a number of constraints inherent to their small size (areas ranging from less than 1 km² to several thousand km²) and to their geographical remoteness from major world centers of activity (for example economies of scale are scarce, affecting their competitiveness, the education system, etc.). In particular, their geographical characteristics (limited land area, reduced plains, strong exposure to sea-related hazards) and human specificities (strong dependence upon subsistence activities and ecosystems) can explain their high sensitivity to environmental changes and to natural disasters. Such features directly generate a series of impacts which, on the continent, would generally be easily attenuated in space and in time (Duvat and Magnan, 2012).

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

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

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

THE PHYSICAL PROCESSES AT WORK

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

Rising sea level

Rising sea level as a consequence of climate change is undoubtedly the most publicized phenomenon, especially for small islands. Catastrophic interpretations badly relay the more prudent scientific conclusions, and certain media announce the impending disappearance of low-lying islands (especially the Maldives, Kiribati and Tuvalu) while others proclaim the imminent flooding of coastal plains that concentrate populations and economic activities. Although such claims can be questionable, because the responses of island systems to climate pressure will be necessarily diverse, it remains an undeniable fact that the sea level has been rising for more than a century due to anthropogenic climate change. Why? First, the increase in the temperature of the lower layers of the atmosphere warms the surface ocean waters, resulting in their expansion. This is combined to the melting of continental ice (mountain glaciers, Arctic and Antarctic ice caps), increasing the volume of ocean water, which, schematically, tends to "overflow". The average rate of sea level rise was 17cm across the globe throughout the twentieth century, corresponding to about 1.7mm/year (Church *et al.*, 2013).

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

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

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

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

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

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

ment (Earth Summit, Rio, 1992) emphasized once again the particular case of small islands. Most recently, during the Third International Conference of the United Nations on Small Island developing States, held in early September 2014 in Samoa, one of the key themes addressed was climate change and, in particular, rising sea level.

Extreme events: hurricanes, distant waves and El Niño

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

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

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

Likewise, the evolution of storms in temperate zones (North and South) and at high latitudes, which remains difficult to predict, should also have an impact on the changes in the sea-related hazards in insular environments. Indeed, it is now clear that the powerful swell produced by these storms can spread over great distances across the ocean and cause significant damage on distant island territories thousands of kilometers from its area of formation (Nurse *et al.*, 2014). For example, in December 2008, distant swells caused significant damage in many states of the Western Pacific like the Republic of the Marshall Islands, the Federated States of Micronesia and Papua New Guinea (Hoeke *et al.*, 2013).

Finally, it is still extremely difficult to predict the evolution of El Niño, while at least four of its manifestations are known to disrupt insular environments. Firstly, the significant changes in surface ocean temperatures that occur during El Niño events are reflected in some regions by marked temperature peaks. They are responsible for devastating coral bleaching events[6] (95 to 100% coral mortality in the Maldives and the Seychelles in 1997-1998). Secondly, El Niño events result in an increase in the number of cyclones in areas usually less exposed, as is the case of the Tuamotu Archipelago in French Polynesia: while the

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

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

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

The rise in the ocean temperature

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

The ocean acidification

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

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

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

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

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

IMPACTS ET VULNÉRABILITÉ DES PETITES ÎLES

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

What impacts are expected?

Climate models do not yet provide accurate evolution scenarios at the scale of different oceanic sub-regions. However, the current predictions, supplemented by available knowledge on the responses of island systems to the different types of natural and human pressures, can allow assessing the main impacts that climate change will have. The effects on the evolution of the islands and of their main coastal ecosystems, coral reefs and mangroves, will be successively addressed below.

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

It is impossible to predict the response of island systems to the pressure resulting from climate change because of the multitude of factors involved and of the complexity of their interactions. These factors can be both natural (sediment reservoirs, storm impacts, responses of coral reefs to the pressure associated with climate change, etc.) and anthropogenic (interference of coastal development with natural coastal processes, impacts of human activities and public policies on ecosystems, etc.). Hence, in the coming decades, a decrease in area of the islands can be expected, particularly for coral islands. A country like the Maldives, where the altitude of 80% of the emerged land area is less than 1m high, will indeed most probably undergo a significant reduction in its area under the effect of sea level rise. However this stress factor has, like the other ones (frequency and intensity of storms, deterioration of the health of coral reefs, etc.), varying impacts from one island to the other, depending on the geomorphological and human context. For example, the islands already affected by erosion or whose coastline is heavily developed will not benefit from any natural mechanism of elevation allowing them to adjust to sea level rise. Such an adjustment mechanism will be possible only if there is an underwater sediment reservoir capable of supplying the shore, but also an area free of any development along the coastline where sediment can accumulate. On one hand, nowadays, these two conditions are only met in a limited number of inhabited islands, but on the other hand, such a natural adjustment mechanism could probably only succeed on certain little- or un-developed Islands.

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

In some cases, a decrease in the area of low islands will probably lead to question their viability, as their resources will become insufficient to meet the needs of their inhabitants. The coastal plains of the higher islands will also be subjected to climate pressures resulting in impacts on the communities that will be all the more stronger as the demographic pressure is high and as food production systems are developed (Nurse *et al.*, 2014).

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

Coral reefs under threat

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

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

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

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

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

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

What is the future for the mangroves?

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

How will climate change impact mangroves? Theoretically, a rise in sea level should cause an inshore migration as the different ecological zones that make up the mudflat also tend to adapt by migrating in this direction. However, beyond the sea level rise, two factors will play a key role: the sedimentation rate and the level of human pressure on the ecosystem. In favourable conditions (active sedimentation and reduced human pressure) the rise in sea level can be compensated by the rising of small scale sea beds. In this case, mangroves remain or continue to expand offshore. The most sensitive areas are undoubtedly those that are already affected by severe erosion, causing the destruction of mangroves, and/or those which have already been degraded by man.

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

9 Sediments produced by previous generations of coral reefs.

What impact on island resource systems?

To make progress in the chain of impacts of climate change and ocean acidification on human communities, the focus is put on the impact of physical disturbances on land (soil, water, flora and fauna) and marine resources (reef and fisheries) of low-lying islands and coastal plains of high mountainous islands.

On land

Land resources are going to decline as a result of various processes (Nurse *et al.*, 2014, Wong *et al.*, 2014). Firstly, the increase in atmospheric temperature leads to increased evapotranspiration[10], causing the soil to dry and an increase in the consumption of brackish shallow groundwater by plants. This groundwater absorption should not be overlooked, as measurements on Tarawa Atoll (Kiribati) have shown that the most common tree, the coconut tree, restored at least 150 liters of water per day to the atmosphere through transpiration. Under these conditions, the expected increase in groundwater pumping by coconut trees and other types of vegetation should significantly strengthen the pressure that is exerted on these reserves that are already used by humans to meet there needs. The degradation of the quality of the soils and the decreasing water resources will further reduce the possibilities of cultivation. Consequently a drop in production should arise, especially for island agriculture, representing a serious challenge regarding food security. An increase in external dependency will follow, especially for rural atolls in many coral archipelagos. Soils will also tend to degrade under the effect of salinization due to rising sea levels and more frequent coastal flooding on the islands and coastal plains that cannot elevate. Moreover, few edible plant species tolerate salt, even though coconut tree can support salt up to a certain threshold beyond which they die. The reduction in exploited areas, especially coconut groves, should reduce the availability of building materials. Also, the gradual evolution of island farming practices towards species that are less resistant to climatic and marine pressures than indigenous species - for example the banana tree being less resistant than the pandanus and the coconut trees - may increase the magnitude and frequency of food shortages (this is what happened for example in the Maldives following the damage caused by the tsunami in 2004) and trade deficits (the case of the West Indies following the passage of Hurricane Dean in 2007) in the future.

Climate change will cause quantitative and qualitative changes in water resources, which depend on several factors. The most important is the sea level, whose elevation will inevitably reduce the volume of underground freshwater reserves. According to the principle of Ghyben Herzberg that governs the functioning of aquifers, any rise in sea level causes a reduction in volume. More frequent or even systematic coastal flooding during high spring tides, are the source of repeated intrusions of salt water into the groundwater, thus contributing to the deterioration of its quality. The islands and coasts under strong coastal erosion should be more affected by the decrease in the volume and quality of underground lenses. Another important factor is rainfall, which determines the rate and frequency of recharging the underground freshwater lens and rivers that cross the coastal plains. To date, there is no reliable mean of forecasting the evolution of rainfalls. Moreover, there are still uncertainties regarding the freshwater resources of certain high islands. It is thus impossible to identify the islands and archipelagos that will be most affected by the degradation of water resources. A reduction in the volume of available water is to be expected in areas where droughts will be more frequent and/or drawn-out. Consequently, the water will become more salty, causing the increase in the frequency and severity of crop mortality peaks (for coconut and taro, in particular) which are already being observed. The removal of water from the groundwater during a drought has the further effect of reducing its thickness, which means that in periods of water shortage, groundwater, which is crucial for the survival of many islanders, may become unfit for consumption. As rainwater tanks on the islands become empty when the drought lasts, this issue could undermine the habitability of certain low-lying islands. Individual access to water should also decrease as a result of the high population growth characterizing these areas.

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

At sea

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

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

It is now feared that due to the combination of the effects of unsustainable development, climate change and acidification, certain archipelagos will no longer be inhabitable within a few decades.

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

This third section highlights the importance of considering the pressures of climate change and ocean acidification in a broader context of anthropogenic pressures. The aim is to show how future threats initially take root in the current issues of "unsustainable development", that is to say, non-viable development, illustrated in particular by the strong deterioration of coastal ecosystems and uncontrolled urbanization. In this case, climate change and ocean acidification play the role in the acceleration of pressure on the living conditions of insular communities.

The case of the coral archipelago of Kiribati (Central Pacific) illustrates this point (Duvat *et al.*, 2013, Magnan *et al.*, 2013). Focus is put on the effects of climate change only, since the effects of ocean acidification are for the moment too complex to determine in the specific case of Kiribati. A brief assessment of the natural constraints and socio-economic changes of the last two centuries can explain what pressures the country is currently facing, and in what manner climate change will amplify them. With the questionable future of these areas and island populations, this demonstrates the major importance of overlapping the physical (climatic and chemical processes, ecosystems, etc.) and human dimensions (cultural relationship to resources and risk, development patterns, etc.) in order to understand these systems in their geographical and historical complexity. In other words, their vulnerability to future environmental changes not only depends on the evolution of the climate/ ocean relationship. This basic reasoning is a fundamental step towards understanding vulnerability in all its dimensions, but also to imagine strategies of adaptation that can be locally relevant, consistent and realistic in their implementation.

Like Tuvalu and the Maldives, Kiribati mainly comprises atolls whose evolution depends on the responses of corals to changes in weather and sea conditions. Its exclusive economic zone (EEZ) is vast (3.5 million km²) and contrasts with the modesty of its land area (726km²), which is also fragmented into a large number of islands. On an atoll, the dominant element is the lagoon, enclosed by a ring of reef islands that are generally less than 1km² in area. They are also not inhabitable on their entire surface due to the presence of mudflats and mangrove swamps, to the strong instability of their coastlines and to very low altitudes in some parts. Summits mainly culminate around 3 to 4m, so the risk of submersion remains very high. As they are young (between 2000 and 4000 years), made of sand and coral debris and exposed to marine processes, their soils are poor and vegetal resources weakly diversified. Water is scarce, brackish (2-3g salt/L) and very sensitive to climatic fluctuations. Water comes from rainfall that infiltrates to form a shallow groundwater lens (from 1 to 2m) proportional in size to the islands. In the southern atolls of Kiribati, the presence of water becomes uncertain during droughts related to El Niño episodes, which can last up to 2 years.

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

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

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

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

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

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

THE KEY MESSAGES TO REMEMBER AND AVENUES TO EXPLORE

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

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

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

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

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