Small islands, ocean and climate

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

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

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

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

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

THE PHYSICAL PROCESSES AT WORK

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

Rising sea levels

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

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

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

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

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

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

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

Extreme events: cyclones, distant swells and El Niño

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

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

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

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

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

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

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

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

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

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

Ocean warming

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

Ocean acidification

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

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

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

IMPACTS AND VULNERABILITY OF SMALL ISLANDS

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

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

What impacts are expected?

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

Reduced island surface area and coastline retreat

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

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

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

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

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

Coral reefs under threat

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

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

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

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

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

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

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

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

[9] Sediments produced by previous generations of coral reefs.

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

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

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

What is the future for mangroves?

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

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

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

What will be the impact on island resource systems?

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

On land

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

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

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

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

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

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

At sea

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

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

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

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

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

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

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

BETWEEN ENVIRONMENTAL CHANGES RELATED TO ATMOSPHERIC CO$_2$ AND UNSUSTAINABLE DEVELOPMENT: THE SYMPTOMATIC CASE OF ATOLLS

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

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

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

Like Tuvalu and the Maldives, Kiribati mainly consists of atolls that evolve based on coral response to variations in weather and sea conditions. Its exclusive economic zone (EEZ) is vast (3.5 million km^2) and contrasts with the modesty of its land area (726 km²), comprising a large number of scattered islands.

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

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

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

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

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

KEY TAKEAWAYS AND AVENUES TO EXPLORE

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

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

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

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

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

REFERENCES

- ARNDT D.S., BARINGER M. O. and JOHNSON M.R., 2010 – *State of the Climate 2009*. Bull Am Meteorol Soc, 91 : 1-222.
- BECKER M.B., MEYSSIGNAC C., LETETREL C., LLOVEL W., CAZENAVE A. and DELCROIX T., 2012 – *Sea Level Variations at Tropical Pacific Islands since 1950.* Global Planet. Change 80-81 : 85-98.
- CAZES-DUVAT V., PASKOFF R. and DURAND P., 2002 – *Évolution récente des deux îles coralliennes du banc des Seychelles (océan Indien occidental).* Géomorphologie, 3 : 211-222.
- CHURCH J.A. *et al.*, 2013 – *Sea Level Change. In Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- CIAIS P. *et al.*, 2013 – *Carbon and Other Biogeochemical Cycles. In: Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- DIAMOND J., 2006 – *Effondrement : comment les sociétés décident de leur disparition ou de leur survie.* Gallimard.
- Di Piazza A., 2001 – *Terre d'abondance ou terre de misère. Représentation de la sécheresse à Nikunau (République de Kiribati, Pacifique central).* L'Homme, 157.
- DONEY S.C., FABRY V.J., FEELY R.A. and KLEYPAS J.A., 2009 – *Ocean Acidification : the Other CO_2 Problem.* Ann Rev Marine Sci 1 : 169-192.
- DUPONT J.-F., 1987 – *Les atolls et le risque cyclonique : le cas de Tuamotu.* Cahiers des sciences humaines, 23 (3-4) : 567-599.
- DUVAT V. and MAGNAN A., 2012 – *Ces îles qui pourraient disparaître.* Le Pommier-Belin.
- DUVAT V., MAGNAN A. and POUGET F., 2013 – *Exposure of Atoll Population to Coastal Erosion and Flooding : a South Tarawa Assessment, Kiribati. Sustainability Science, Special Issue on Small Islands.* 8 (3) : 423-440.
- V. DUVAT and A. MAGNAN, 2014 – *Des catastrophes… « naturelles » ?* Le Pommier-Belin.
- ÉTIENNE S., 2012 – *Marine Inundation Hazards in French Polynesia : Geomorphic Impacts of Tropical Cyclone Oli in February 2010.* Geological Society, London, Special Publications, 361 : 21-39.
- GATTUSO J.-P. and HANSSON L., 2011 – *Ocean Acidication.* Oxford University Press.
- GATTUSO J.-P., HOEGH-GULDBERG O. and PÖRTNER H.-O., 2014 – *Cross-Chapter Box On Coral Reefs. In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A : Global and Sectoral Aspects.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- GATTUSO J.-P., BREWER P.G., HOEGH-GULDBERO. G, KLEYPAS J.A., PÖRTNER H.-O. and SCHMIDT D.N., 2014 – *Cross-Chapter Box on Ocean Acidification. In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A : Global and Sectoral Aspects.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- GLYNN P.W., MATÉ J.L., BAKER A.C. and CALDERON M. O., 2001 – *Coral Bleaching and Mortality in Panama and Ecuador during the 1997-1998 El Nino Southern Oscillation Event : Spatial/Temporal Patterns and Comparisons with the 1982-1983 Event.* Bulletin of Marine Sciences, 69 : 79-109.
- HOEGH-GULDBERG O., 1999 – *Climate Change, Coral Bleaching and the Future of the Worlds' Coral Reefs.* Marine and Freshwater Resources, 50 : 839-866.
- HOEGH-GULDBERG O., 2011 – *Coral Reef Ecosystems and Anthropogenic Climate Change.* Regional Environmental Change, 1 : 215-227.
- HOEGH-GULDBERG O., CAI R., BREWER P., FABRY V., HILMI K., JUNG S., POLOCZANSKA E. and SUNDBY S., 2014 – *The Oceans. In Climate Change 2014: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- HOEKE R.K., MCINNES K. L., KRUGER J.C., MCNAUGHT R. J., HUNTER J.R. and SMITHERS S.G., 2013 – *Widespread Inundation of Pacific Islands Triggered by Distant-Source Wind-Waves.* Global and Planetary Change, 108 : 128-138.

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