CYCLONES AND CLIMATE CHANGE IN THE SOUTH PACIFIC

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RÉSUMÉ. — Cyclones et changement climatique dans le Pacifique Sud. — Les cyclones tropicaux se manifestent de manière relativement fréquente dans tout le Pacifique Sud, modifiant les récifs de coraux et les îles coralliennes basses. Ces cyclones peuvent, sur les récifs et îles coralliennes, à la fois donner lieu à des accumulations de blocs et de sable sur certaines parties tout en endommageant et érodant d’autres parties. Beaucoup d’îles coralliennes doivent leur existence à l’accumulation de ces matériaux durant les orages tropicaux. La localisation des cyclones est fortement influencée par le phénomène El Niño (ENSO) ; ils sont plus abondants dans le Pacifique Est durant les phases d’El Niño. La fréquence des cyclones ne devrait vraisemblablement pas varier dans le futur, néanmoins leur force devrait être fortement influencée par l’amplification du changement climatique et l’élévation des températures à la surface des mers. Le résultat serait probablement une augmentation des cyclones des catégories 4 et 5 avec pour conséquence des dommages encore plus localisés sur les récifs coralliens et les îles qui leur sont associées. Alors que ces cyclones ne dévasteront pas les récifs à l’échelle mondiale, la synergie entre leurs dégâts localisés et de plus importants effets de l’augmentation des températures de surface des mers, d’acidification des océans et d’élévation du niveau des eaux, fait peser de graves menaces sur l’existence à long terme des récifs coralliens actuels. Les gestionnaires des ressources coralliennes n’ont pas d’autre possibilité de combattre les cyclones que de s’associer aux campagnes contre les changements climatiques et les gaz à effet de serre ; néanmoins ils peuvent aider en rendant les récifs plus résistants et résilients aux dégâts des cyclones en menant une action sérieuse visant à réduire les dégâts directs et localisés d’origine anthropique.

SUMMARY. — Tropical cyclones occur relatively frequently throughout the South Pacific with resultant changes to coral reefs and low lying coral islands. Cyclones can result in both accumulation of coral rock, rubble and sand to parts of coral reefs, whereas there can be severe damage and erosion to other parts of reefs and islands. Many coral reef islands owe their existence to the accumulation of material during tropical storms. The location of cyclones is strongly influenced by the El Niño Southern Oscillation, with more in the Eastern Pacific during El Niño events. The frequency of cyclones is unlikely to alter significantly in the future, however the strength of these cyclones will be strongly influenced by increasing global climate change and rising sea surface temperatures. The result is that there will probably be more large category 4 and 5 storms, which will result in even more localized damage to coral reefs and associated islands. While these cyclones will not be devastating for reefs at ocean scales, the synergy between their localized damage and more widespread effects of increasing sea surface temperatures, ocean acidification and rising sea levels, pose major threats for the long term existence of coral reefs as they occur today. Coral reef resource managers have no mechanisms to combat cyclones other than by joining global campaigns against climate change and the release of greenhouse gases; however they can assist in making reefs more resistant and resilient to cyclone damage by taking serious action to reduce direct and localized anthropogenic damage.

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WHAT IS A CYCLONE\(^3\)?

Cyclones are strong swirling wind systems that originate from a low pressure system that develops as a storm over the ocean. Cyclones form when the sea surface temperatures exceed about 28°C to a depth of at least 60 m. Evaporation is intense and produces substantial cloud masses. As the hot air rises it is replaced by cooler air coming in underneath. This whole complex rises swiftly to high altitudes in a swirling configuration that is influenced by the Coriolis force (vortex rotating clockwise in the Southern Hemisphere, and counter clockwise in the Northern Hemisphere).

The cloud mass of a cyclone can be more than 1000 km in diameter (Figs 1, 2). The ‘eye’ of the cyclone, often 20 to 50 km in diameter, is the central part of the formation and it is relatively calm with low wind speeds and minimum atmospheric pressure, frequently well under

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3 The word ‘cyclone’ is used for clockwise tropical storms south of the Equator in the Indo-Pacific oceans; ‘typhoon’ is applied to counter-clockwise tropical storms in the North Pacific; and ‘hurricane’ describes storms in the Atlantic Ocean, which are counter-clockwise storms in the North, including the wider Caribbean.
Figure 2. — This image of cyclone Oli taken on 3rd February 2010 shows the extent of this large system as it approached from the East towards the Society islands, French Polynesia.

900 hectopascals (HPa). The wall of the cyclone, around the eye, features the strongest winds and the heaviest precipitation. There is also usually heavy rainfall produced from the spiralling fringe of the cyclone (Fig. 3).

Figure 3. — A diagrammatic representation of cyclone structure as it spirals in a clockwise direction in the Southern Pacific. The damage to reefs results from large waves and battering by broken corals and rubble, often cascading down reef slopes.
Various cyclone classification systems are used depending, amongst other things, on whether wind speeds are measured over 10 minutes or one minute to express average wind speed. Three weather centres have been officially designated in the South Pacific to monitor tropical depressions: Nadi (Fiji; www.met.gov.fj); Brisbane (Bureau of Meteorology, Australia www.bom.gov.au); and Wellington (New Zealand; www.metservice.com). We refer to the classification used by Nadi that distinguishes between ‘tropical cyclones’ on a scale of 1 to 5 with sustained wind speeds recorded over a 1 minute period ranging from 53 to over 198 km. h\(^{-1}\) (Table I). The term ‘tropical storm’ is however often used when wind speeds are between 63 and 117 km. h\(^{-1}\), while the term ‘cyclone’ applies when higher speeds occur (English-language usage favours the use of the term ‘typhoon’ for those storms generated to the North of the Equator; and ‘hurricane’ to storms generated in the Atlantic Ocean). The Saffir-Simpson scale classifies them into five categories depending on the wind speed and the height of storm surge: category 1: 119 km. h\(^{-1}\) and \(h < 1.5\) m, to category 5: 250 km. h\(^{-1}\) and \(h > 5.5\) m. In French, these depressions are referred to with equivalent terms: ‘tempête’, ‘typhon’, ‘ouragan’ or ‘cyclone’. The storm surge raises the sea level by 2 to 5 m making the wave sets even more destructive on reef flats and coastal areas, with waves reaching a height up to 12 m maximum.

Tropical cyclones are predominantly initiated within the Equatorial Zone and then spin out under the influence of the Coriolis force. These developing ‘cyclones’ contain little energy while in the zone between 7° N to 7° S, and predominantly have few impacts on coral reefs. However as they move out of the Equatorial zone, they gain energy and become destructive to coral reefs and islands beyond 7° latitude (Fig. 4; Scoffin 1993).

The South Pacific area is a cyclone-generating zone, usually between December and April, but it is not the most significant one in the world. Some 11 cyclones occur there annually on average as compared to 30 in the Northwest Pacific and 12 in the North Atlantic / Caribbean area.

In the South Pacific, cyclone formation is strongly influenced by ‘El Niño’ climate variations, which cause an abnormal warming of the surface ocean layers of the Equatorial Zone.

![Tracks and Intensity of All Tropical Storms](image)

Figure 4. — Cyclones are major structuring forces for coral reefs, however, the effects are predominantly observed outside a zone 7° N to 7° S in relation to the Equator. This figure shows the tracks of tropical cyclones over the past decades with a clear band of minimal activity near the equator. Figure courtesy of NASA, USA.
of the Western Pacific and off the coast of Peru. The region’s meteorology is dominated by the meteorological condition called the ‘Southern Oscillation Index’, which is the pressure difference between Tahiti and Darwin. When this difference is negative, leading to higher pressure, it produces an ‘El Niño’ event. When the difference is positive, the result is a ‘La Niña’ event. The link between the oscillation and El Niño is so strong that the two terms are brought together to designate the event known as ENSO (El Niño Southern Oscillation). Under ‘normal’ circumstances, the strong trade winds blow from the East and induce a rise in the Pacific Ocean water level of approximately 60 cm in the West compared to the Eastern Pacific, inducing a powerful upwelling of deep cold water along the South American coast flowing up from the deep Antarctic (the Humboldt Current). This upwelling of nutrient rich waters results in large plankton blooms and resultant major fisheries. During strong La Niña periods, these normal conditions are accentuated; this phase is referred to as the ‘cool’ phase such that the central and eastern Pacific Ocean waters are cooler than those in the West. Conversely, during an El Niño period, the weakening or disappearance of the trade winds blowing to the West reverses the oceanic gradient, it blocks any major upwelling off the coast of Chile and brings warmer waters into the central and even eastern Pacific; this is a ‘warm’ phase. The principle cyclone-producing area then moves eastwards reaching French Polynesia with accompanying high rainfall, while drought conditions begin to affect the Western Pacific, including Papua New Guinea, Northern Australia and New Caledonia. During the El Niño periods of 1982-83 and 1997-98, the El Niño was coupled with many cyclones in the central and eastern Pacific. Once they have begun to move out of the Equatorial generation zone, cyclone trajectories are unpredictable and can move at speeds of up to 15 m.s⁻¹.

The frequency of ENSO events varies from between two and seven years. The El Niño periods correspond to higher water temperatures than normal, but also precipitation that will modify salinity. The corals record the events within their skeletons and their subsequent examination has made it possible in some regions to determine the timing of historical ENSO events. Using these techniques, Boiseau et al. (1998) suggested that there have been 36 El Niño phases in French Polynesia over a period of 137 years (1853-1989) by inspecting a core sample from a large Porites coral; a mean of 3.8 year intervals.

THE EFFECTS OF CYCLONES ON CORAL REEFS

Cyclones are major ‘architects’ of coastal zones, in particular for the morphology of low coral islands which they fashion because their effects concern not only the reefs, but also the land. In the tropical islands of the South Pacific, the coral reefs provide the limestone substrate material that is broken up and transported by cyclones. While cyclones are a cause of erosion, they are also responsible for the accumulation of coral rubble (blocks and sand) that form or accentuate the beaches and banks of small islands and atolls. The action of storms and cyclones over the centuries has created these coral islands or ‘motu’ which then become covered in vegetation growing on a foundation that may date back several thousand years (reef conglomerate and fossilized reefs from 6000 to 1000 BP [before present]; Pirazzoli & Montaggioni, 1988). It has been estimated that almost one third of the surface area of Pacific atoll coral rims results from the accumulation of materials shifted by cyclones (Davies & Hopley, 1983; Montaggioni, 1985, 2007). The effects of cyclones on atolls are well documented as the result of events affecting a number of islands: Funafuti (Maragos et al., 1973); Jaluit (Blumenstock, 1961); and Raroia (Newell & Bloom, 1970).

The ramparts made of accumulated blocks, sand and rubble are built during cyclones, sometimes as successive rows from the reef outwards toward the land. A study on the Australian Great Barrier reef very clearly documented the creation of these block ramparts that stretch over 400 m, evidence of 22 cyclones between 6000 BP and the present (Nott & Hayne, 2001), as well as the creation, or erosion, of small islands.

Cyclones are also responsible for removing blocks from atoll reef front areas and carrying them to the reef flat. Such mega-blocks weighing several hundred tonnes can be seen in the Tuamotus at Rangiroa (Bourrouihl-Le Jan & Talandier, 1985) and indeed the bulky blocks
deposited on the reef flat of Nukutipipi atoll (Tuamotu) during cyclone Orama in 1983 (Salvat & Salvat, 1992).

Cyclones have a major destructive impact on large areas of reef, often more extensively on the windward side of the depression than on the opposite side. The destruction is even worse when the cyclone trajectory is the same as the direction of the dominant swell. The morphology of coral colonies provides them with varying degrees of innate resistance to the very varied hydrodynamic forces involved. The thin branching and plate like corals of genus Acropora are amongst the first to be broken, whereas the massive forms (Porites, Pocillopora) or encrusting forms (Montipora) offer better resistance (Stoddart, 1971; Woodley, 1980; Ogden, 1992). But when a cyclone occurs, the direct damaging action of strong waves and currents is exceeded by the ‘wrecking ball’ effect of the broken colonies that are thrown against undamaged colonies, often uprooting them. The ‘to-and-fro’ movement of the blocks and rubble broken by the swell can literally ‘shave’ the top of layers of unconsolidated coral substrate of the reef. The loosened coral blocks and rubble can ‘avalanche’ down the reef slope to a depth where the slope meets the ocean floor. This can be to depths of 50 m or more (Harmelin-Vivien, 1994).

The effects of cyclones on reefs in the strictest sense have been well described in ‘before-and-after’ studies carried out by Harmelin-Vivien & Laboute (1986) during the 6 cyclones that affected the islands of French Polynesia in 1982-83 (Dupon, 1986). The destruction of coral cover on the outer slopes of the reefs varied from 50 to 100% depending on depth, with maximum coral breakage at 6 m, corresponding to the wave ‘plunge point’. On relatively steep slopes (45% slope), the damage was largely due to avalanches of broken colonies ploughing off the top of the reef, whereas on the less steep outer slopes the broken colonies were thrown up onto the reef flat. The most destructive effects occur when the cyclone trajectory follows the same as the direction of the dominant swell. Similarly, great damage occurs when cyclonic waves impact on parts of the reef that are usually sheltered from the dominant trade wind swells. Such areas are often covered by large amounts of fragile branching corals. Harmelin-Vivien (1994) published an excellent review of the effects of cyclones on coral reefs by documenting more than 40 events between 1905 and 1991, including eight in the Pacific for which there were before-and-after studies.

The associated high rainfall leads to a reduction in salinity (Kierspe, 1981), increases in suspended sediments, and higher turbidity; these all are damaging for corals and reefs (Furnas, 2003). On high islands, the often heavy cyclone-induced rainfall can result in large amounts of terrigenous sediments and other material such as trees, causing pollution that is particularly damaging to fringing coral reefs (Kierspe, 1981). During particularly powerful cyclones, the areas flooded by the inflow and outflow of water masses will worsen this type of pollution, sometimes with effects comparable to the flooding caused by tsunamis. Several authors have noted a decline in fish communities in shallower waters as they migrate to deeper areas following such events; this exceeds any increase in mortality in these areas (Bortone, 1976; Bouchon et al., 1991). On the Great Barrier Reef, van Woesik et al. (1991) observed a reduction in plankton-eating species which have a specific habitat within coral colonies, especially the more fragile branching species. Other attached and non-attached benthic organisms (sponges, gorgonians, molluscs, echinoderms) are also damaged by the effects of cyclones by being uprooted or moved from the substrate and carried to reef flats and lagoons (Harmelin-Vivien, 1994).

The issue of reef rehabilitation after cyclones has produced abundant literature (Grigg, 1983; Hughes, 1989; Salvat, 1992; Done, 1992). It has again become topical, together with the concept of resilience. The problem of whether reefs will return to a similar structure and community composition as previous reef, or indeed whether coral communities will be succeeding each other over time is at the heart of the reef survival debate, if all the effects of climate change, in addition to cyclones, are considered.

**PREDICTIONS OF CYCLONE INCIDENCE RELATED TO CLIMATE CHANGE**

An initial assessment would indicate that the warming of the ocean waters as a result of climate change will most probably generate more frequent cyclones, but a number of factors are involved and they make the analysis more complex and vary the predictions.
Contradictory assertions have been made recently about the relationship between recent cyclones (number and strength) and the beginning of climate change processes. This is partly paradoxical because most climate change predictions agree that the number of cyclones will remain approximately similar, but that their probable intensity will increase. Webster et al. (2005) consider that the number and duration of cyclones are generally stable and have been for 35 years on a global scale, but that the generation of category 4 and 5 hurricanes (the maxima on the Saffir-Simpson scale) has almost doubled since 1970 (Fig. 5). This was also confirmed by Hoyos et al. (2006) with a correlation that these strongest cyclones were due to rising tropical sea surface temperatures. Elsner et al. (2008) re-analysed satellite data since 1980 and confirmed a similar global increase of these category 4 and 5 extreme cyclones. Similar confirmation came from Nicholls et al. (1998) based on cyclones within the Australian region; and parallel observations have been recorded, in particular in the North Pacific, the South-west Pacific and the Indian Ocean.

In February 2010, the expert group on the impacts of climate change on cyclones formed by the World Meteorological Organization (WMO; www.wmo.int), concluded that, on a planetary scale, cyclones would be as frequent or less numerous than at present, but that their intensity (wind speeds increased by 2 to 11%) would be increased, confirming a warming theory (Knutson et al., 2010). These results agree with the IPCC’s previous predictions (IPCC, 2007) and with the predictions covering eastern Australia (Walsh et al., 2002). Nevertheless the frequency of cyclones in climate change predictions is very debatable.

The occurrence and frequency of cyclones will be variable in the various parts of the South Pacific region depending on ENSO. During La Niña events, cyclones will predominantly occur in the western Pacific and on the Australian coasts but will not reach the central

![Figure 5](image-url)

Figure 5. — This shows that the proportion of intense hurricanes has increased since 1970 in the Atlantic Ocean, while the number of hurricanes has not changed significantly. The graphs of hurricane incidence and intensity are combined into 5 year periods, with projections to 2019. Adapted from Webster (2005); dashed lines show significant linear trends.
and eastern Pacific. On the other hand, during El Niño events, the cyclone-generating zone will move eastwards to cover the Cook Islands and French Polynesia, leaving calm to reign in the western Pacific. According to Izumo et al. (2010) sea surface temperature and winds in autumn in Indonesia are correlated with an El Niño event which will occur about 14 months later.

EXPECTED EFFECTS OF FUTURE CYCLONES AND SYNERGISTIC EFFECTS

The effects of cyclones on coral reefs are known from past observations. Reefs usually recover very well from the impact of such natural events, especially when they have not been subject to human disturbance and when the climate is stable. What is required, therefore, is to consider the effects of possibly more frequent and more powerful cyclones. The distinction is not easy to make, but we should certainly take into consideration the combined effect of these two factors in some areas. We should also examine the effects of synergy between the cyclone factor and other climate change parameters (rising temperatures, sea level rise and ocean acidification are the most significant stresses).

The risk of increased frequencies of destructive cyclones on reefs would result in a loss of resilience, in other words, after a series of events in close succession, reefs would not have sufficient time to regain their initial state. In such a scenario, a change in the coral communities would occur, favouring massive resistant species over more fragile forms (Done, 1999; Hughes et al., 2003). Additionally, when cyclones occur in close succession in summer seasons, the algal populations would become predominant over the coral colonies, resulting in smothering of small colonies. Increased cyclone intensity would lead to more widespread habitat destruction, both in terms of geographical surface area concerned, and of the depth range. Indeed, for the majority of category three or four cyclones on the Saffir-Simpson scale, the direct damage from hydrodynamic action on coral communities is limited to approximately the first 10 to 20 metres of depth.

In the Pacific, geography is a factor that should be factored in when the effects of cyclones are considered within the framework of climate change predictions. A likely scenario is that cyclones will probably not be more frequent, but will be more powerful. It has also been seen that the occurrence of cyclones in the Pacific and their location is closely linked to the ENSO cycle and El Niño years. In the ‘normal’ situation and during the cooler La Niña phases, cyclones are relatively few in number and limited to the western Pacific. Conversely, during the warmer El Niño period, the cyclone-generating cell moves eastwards and cyclones extend over the central Pacific (Samoa, Tonga, Cook Islands, French Polynesia) and can be more frequent. This part of the central Pacific is where reefs are most likely to be affected by increasing cyclone frequency, whether or not these events are more intense, as ENSO changes and El Niño events become more frequent. The damage in coral areas will be exacerbated by the fact that the reefs are not accustomed to cyclones, which have been very infrequent for a little more than a century.

These are the most worrying synergistic aspects. Sea level rise will be beneficial for reefs, as corals will colonize the currently scoured reef flats and fringing reefs will be able to gain ground over the shoreline. But this higher sea level during cyclones will profoundly modify the island coastal morphology and even totally reshape the above-water parts of the atolls. It should be remembered that a sea level of +1 m existed in the Pacific between 6000 and 1500 BP (Pirazzoli & Montaggioni, 1988) and that the small islands and atolls (‘motu’) did not exist at that time. As stated earlier, the bioclastic elements forming them were introduced mostly by storms following the fall in sea level after 1500 BP. Despite the fact that coral reefs will continue to grow in height during the rise in sea level, as predicted by climate change models, this growth will occur with some delay. Coral growth rates are variable and if only the values established from Australian reefs are used for reference purposes, the scales involved will be between 2 m and 5 m per millennium (Hopley, 1982) or between 1.3 and 14.2 m per millennium (Davies et al., 1985). Paulay & McEdward (1990) consider that a standard value of 4 m per 1000 years is the norm. If the rise in sea level was suddenly the 59 cm (IPCC 2007) worst-case scenario which is already an under-estimated prediction, it would take some 150 years for the reef to rebuild itself to just below the water level. As the water height is always above the top
off the reef, cyclones would have a considerable destructive impact on the above-water parts of atolls or coastal zones bordered by reef complexes. This may not concern the reefs themselves, but would be catastrophic for islands, as their very existence is threatened, including the human communities that live and depend on them. Allison et al. (2009) produced an update to include the latest climate research since the latest IPCC (2007) report. They observed that “satellite measurements show sea-level is rising at 3.4 mm per year since these records began in 1993. This is 80% faster than the best estimate of the IPCC Third Assessment Report for the same period”. Also that “Accounting for ice-sheet mass loss, sea-level rise until 2100 is likely to be at least twice as large as that presented by IPCC AR 4, with an upper limit of approximately 2 m based on new ice-sheet understanding”. In such a case, there will be no possibility for low coral islands (atolls) to re-establish and exist after major cyclones.

Sea surface temperature rise will have destructive synergetic effects with cyclones, even if there are no increases in cyclone incidence. Nevertheless, Allison et al. (2009) conclude that “estimates of ocean heat uptake have converged and are found to be 50% higher than previous calculations” noting that “global ocean surface temperature reached the warmest ever recorded for each of June, July and August 2009”. Irrespective of the relation between rising sea temperature and cyclones (frequency and intensity), rising temperatures alone will lead to bleaching events followed by more frequent coral mortality (Hoegh-Guldberg, 1999), which in turn would considerably weaken coral community resistance to attacks by more intense cyclones, even if they are not more frequent. The same can be said for increasing ocean acidification which, if it changes in the way predicted by the IPCC, would be likely to drastically diminish the calcification capacity of corals (Salvat & Allemand, 2009).

REMEDIING THE EFFECTS OF CYCLONES ON CORAL REEFS

If climate change predictions prove accurate, cyclones alone will not pose major increased stresses for coral reefs, because cyclone frequency, per se, is not predicted to be more frequent. However, more frequent intense cyclones will result in extreme localized damage. This does not affect the central Pacific area, as stated above. The issue is not one for coral reef managers to try and combat cyclones, except by working to counter their causes in a broader setting with the campaign against climate change. The other essential factors (sea level rise, temperature rise, ocean acidification) and their effects, like cyclones, cannot be countered by any specific action. If climate change predictions prove reliable, the reefs will suffer the impacts of the factors outlined above.

The only management action that can be taken, therefore, is to ensure that coral reefs are in good health with greater resistance and resilience to the influence of these factors. An already very broadly mooted recommendation is to reduce or indeed eliminate as far as possible all causes of human damage that weaken reef communities that have to withstand the above-mentioned disturbances (Wilkinson, 2008). Another potential management action is to ensure that remote uninhabited coral reefs gain the maximum protection from outside human stresses by being declared as highly protected areas (Salvat & Wilkinson, 2008). Considering the many stresses that threaten the existence of coral reefs, cyclones will pose another threat, and not the major hazard. However, for the existence of low islands and the inhabitability of the coastal zones of high islands surrounded by coral ecosystems and their populations, it is the primary factor.

REFERENCES


